4 Report No. 268 Math

STORAGE OF ANALOG VARIABLES IN DELAY LINES

by

LAWRENCE H. WALLMAN

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DEPARTMENT OF COMPUTER SCIENCE · UNIVERSITY OF ILLINOIS · URBANA, ILLINOIS

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1. INTRODUCTION

The storage of analog variables has always presented a problem. A novel method for solving this problem was first suggested by W. J. Poppelbaum, D. Aspinall, and M. Faiman. This method for storing analog voltages has been developed under the guidance of W. J. Poppelbaum.

The method suggested and developed is essentially that shown in Figure 1. The WRITE signal is a single pulse which occurs at a time corresponding to a voltage level on the periodic CLOCK RAMP as shown in Figure 1. The WRITE signal can be generated by using a voltage comparator which gives an output pulse when the CLOCK RAMP is equal to a D.C. voltage level. The HARMONIC clock signal of Figure 1 is a harmonic of the CLOCK RAMP, that is, the same number of clock pulses always occur during each ramp. The HARMONIC clock gates WRITE to the delay line, thus quantizing the levels on the CLOCK RAMP. This pulse circulates in the delay line loop with the same frequency as the CLOCK RAMP. The feedback in the delay line is gated by HARMONIC clock and thus eliminates any drift in the delay time. Thus, the circulating pulse always represents the same quantized voltage on the CLOCK RAMP. The D.C. voltage can be recovered by using the ramp to charge a capacitor and stopping this charging at the time coincident with the stored pulse.

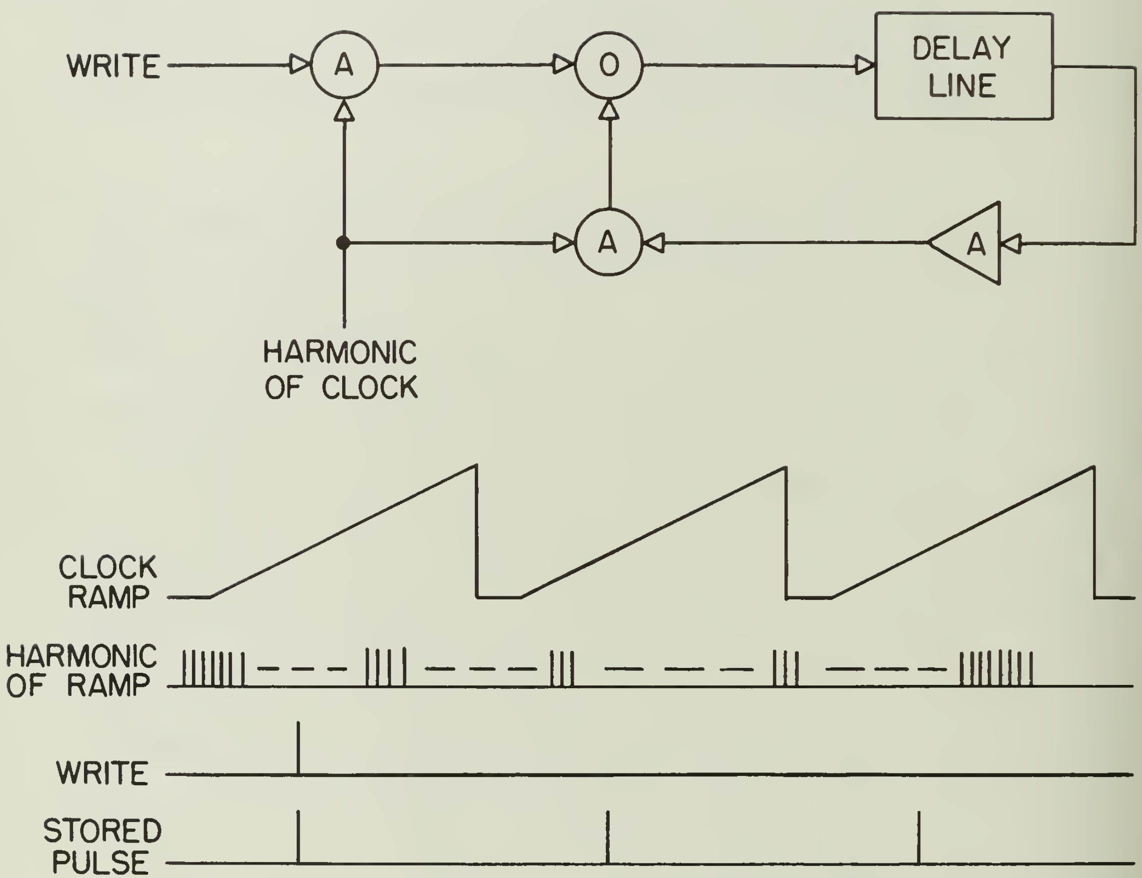


Figure 1. Storage by Reciprocating Delay Line

The accuracy of such a system can be determined by noting the number of clock pulses which occur during the ramp cycle. If there are p clock pulses during the ramp cycle then the maximum time which can elapse before the delay line is re-triggered is equal to one clock pulse; furthermore if there are n clock pulses in the useful portion of the ramp (i.e. excluding any fly back and hold off time) the maximum error in volts which can occur will be $\pm$ 1/n x 100% of the total ramp voltage swing. Therefore the storage system will be accurate to $\pm$ 1/n x 100%.

The circuits for a single storage unit system were originally designed by D. Aspinall. This system was capable of only a +5 volt to -5 volt range of storage and was not sufficiently stable. By unstable it is meant that the delay of the delay line was not constant enough with time to keep the phase relation with the clock ramp. That is, when the period of the clock ramp is different from the delay of the delay line by more than one clock pulse time the system loses synchronization and all stored information is lost.

The initial system which was in the form of a feasibility proof, has been expanded to four storage cells and has been made stable enough to retain stored information for at least eight hours and probably much longer. Thermal influences proved to be of greatest importance in achieving stability.

The purpose of this thesis is to explain how this system works. The system is called "PHASTOR" because the stored information is actually a phase and not the actual input voltage. The aim also was to investigate several delay lines which could be used as the storage circuits and determine which of these were best suited to this purpose.

2. OPERATION OF PHASTOR SYSTEM

The block diagram of Phastor is shown in Figure 2. The main sections of the diagram are (1) the ramp generator, (2) the control circuit, (3) the sample and hold, and (4) the analog (phase) memory units.

The ramp generator generates the ramp clock shown in Figure 2 and Figure 3. This generator is driven by a mod 125 counter which in turn is driven by the harmonic of the ramp clock frequency generator. The harmonic of the ramp clock generator is a crystal-controlled oscillator. The ramp clock rises from -10v to +10v for one hundred of the ramp clock harmonic pulses and returns and stays at -10 volts for twenty-five more pulses. Since there are 100 pulses per ramp the accuracy of this system is $\pm 1\%$.

The control circuit gates one pulse from the comparator (amplitude-to-phase converter) into one of the analog memory units. This gating is effected in the following manner. With the flip-flops in the control circuit set to the beginning state (i.e. C2 = C3 = 1) and the first flip-flop reset, the "INITIATE STORE" button can be pressed. This causes flip-flop Number 1 to flip which in turn causes flip-flop Number 2 to change state. Flip-flop Number 2 changes state only on a zero to one transition at the input. At this point no more outputs from flip-flop Number 1 can

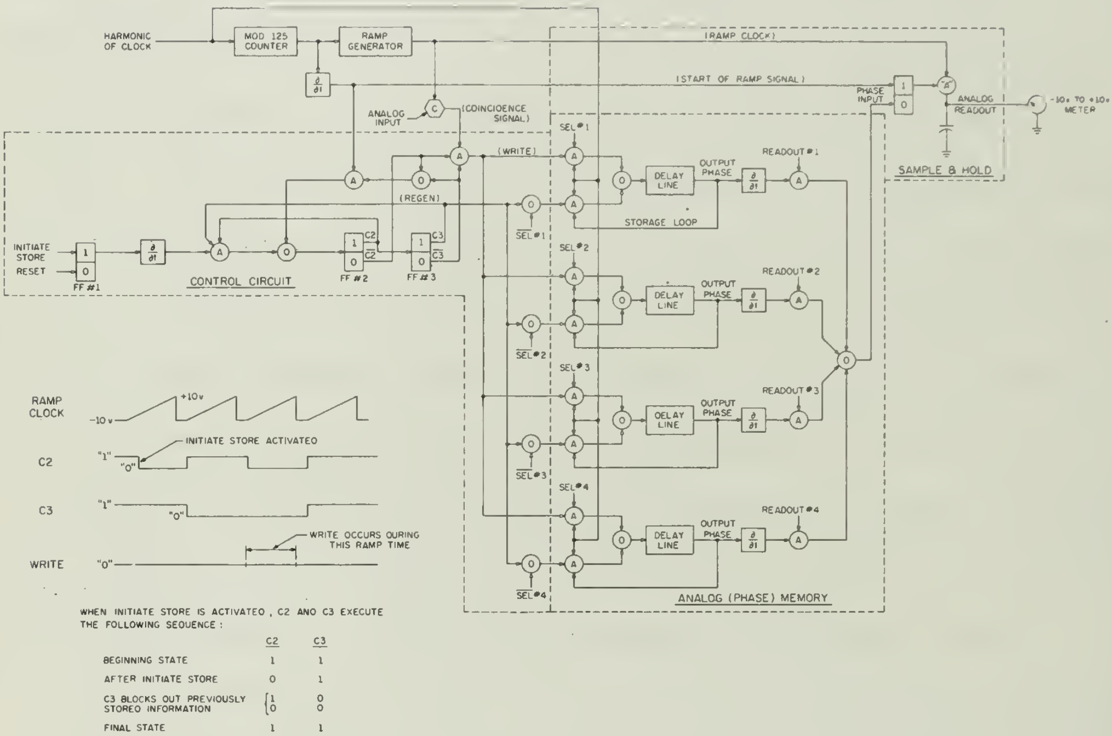


Figure 2. Block Diagram

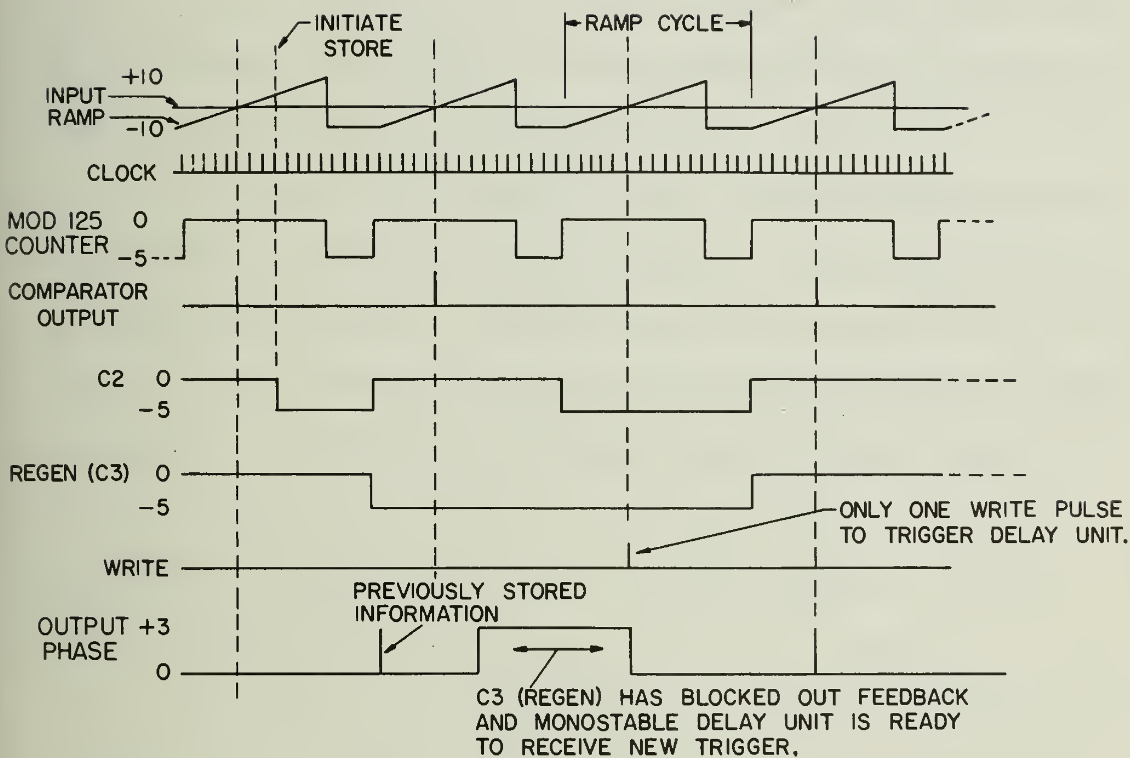


Figure 3. Phastor Waveforms

trigger flip-flop Number 2 since the AND gate will not let them through. However, the output of the mod 125 counter is now gated to the input of flip-flop Number 2 and since the ramp starts on the zero to one transition of the counter flip-flop Number 2 changes state at the start of each ramp. So, flip-flop Number 2 changes state when the "INITIATE STORE" button is pushed and at the start of each ramp after that. Flip-flop Number 3 changes state also only on zero to one transitions, and it is driven directly by the one side of flip-flop Number 2. Therefore flip-flop Number 3 changes state only at the start of the first ramp after the INITIATE STORE button is pressed and after the third ramp and so on.

This sequence can be summarized as follows:

System State	Gating Sequence	
	C2	C3
Beginning state	1	1
State after initiate store is pressed and before start of subsequent ramp	0	1
State during first ramp	1	0
State during second ramp	0	0
State during third ramp	1	1

After the start of the third ramp, the output of the counter is no longer gated to the input of flip-flop Number 2. Flip-flop Number 2 can receive a trigger only from flip-flop Number 1 and therefore the sequence stops. In other words, flip-flop Number 2 and Number 3 act as a MOD 4 counter, which counts the INITIATE STORE button signal and the beginnings of the next three ramps, and then stops. The single pulse from the comparator is gated to the delay line during the second ramp after the pressing of INITIATE STORE, since during this time $\overline{C3}$ = $\overline{C3}$ = 1 and therefore the gate on the comparator output is open. At the start of the first ramp after the beginning of the sequence, C3 = 0 which prevents the feedback pulse in the analog (phase) memory from re-triggering the delay line. This condition persists until after the line is triggered by the new compare pulse. After the ramp time during which the compare pulse occurs, C3 = 1 and allows feedback.

In order to select the particular storage cell in which the analog voltage is to be stored sel # i must be a logical one and $\overline{\text{sel \# i}}$ must be a logical zero. The other cells must have sel # j = 0 and $\overline{\text{sel \# j}}$ = 1 in order to preserve the feedback path and prevent erroneous triggers. In this case, i, j = 1, 2, 3, 4 and i $\neq$ j.

The SAMPLE and HOLD circuit simply lets the ramp charge the capacitor until the stored pulse occurs. At this instant the voltage on the capacitor represents the voltage which was originally stored. The gating of the output of the storage cells is done by

means of an AND on the output of each cell. The second input to these AND's is READOUT # i. READOUT # i must be a logical one in order to read the information out and READOUT # j must be a logical zero.

2.1 Oscillator

The crystal-controlled oscillator is shown in Figure 4. This oscillator and pulse shaper generates the harmonic of the ramp frequency. The circuit is a Colpitts-type oscillator and uses clipping and level shifting to form the output pulses. The output pulses are Clock 1, 0 to +10v and Clock 2, -5 to 0v. The frequency of these pulses is 330 KHz with a duration of 0.4 μsec. The two different levels of clock are needed because the circuit used for the storage cell requires a positive signal, while the mod 125 counter requires a -5v to 0v signal to operate.

2.2 Mod 125 Counter

The mod 125 counter is made from three mod 5 counters connected in series. The circuits used are TI SN7470 integrated circuit J-K flip-flops.

The truth table for the J-K flip-flop is shown below.

t_n		t_{n+1}
J	K	Q
0	0	Q_n
0	1	0
1	0	1
1	1	$\overline{Q_n}$

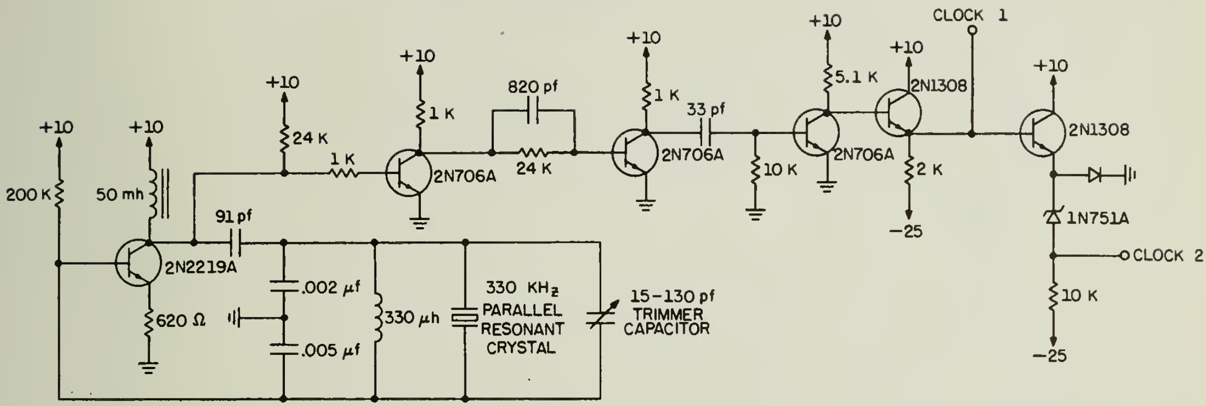


Figure 4. Oscillator

There are eight possible states for this counter but only five of them are used for the modulo five counter shown in Figure 5. The possible states for the counter are listed below.

Possible States

Q_1	Q_2	Q_3
0	0	0
0	0	1
0	1	0
0	1	1
1	0	0
1	0	1
1	1	0
1	1	1

The sequence of these states used and the corresponding inputs are shown below.

State at t_n			Input at t_{n+1}		
Q_1	Q_2	Q_3	J_1K_1	J_2K_2	J_3K_3
0	0	0	11	00	00
1	0	0	11	11	00
0	1	0	11	00	00
1	1	0	11	01	10
0	0	1	01	00	01
0	0	0	11	00	00

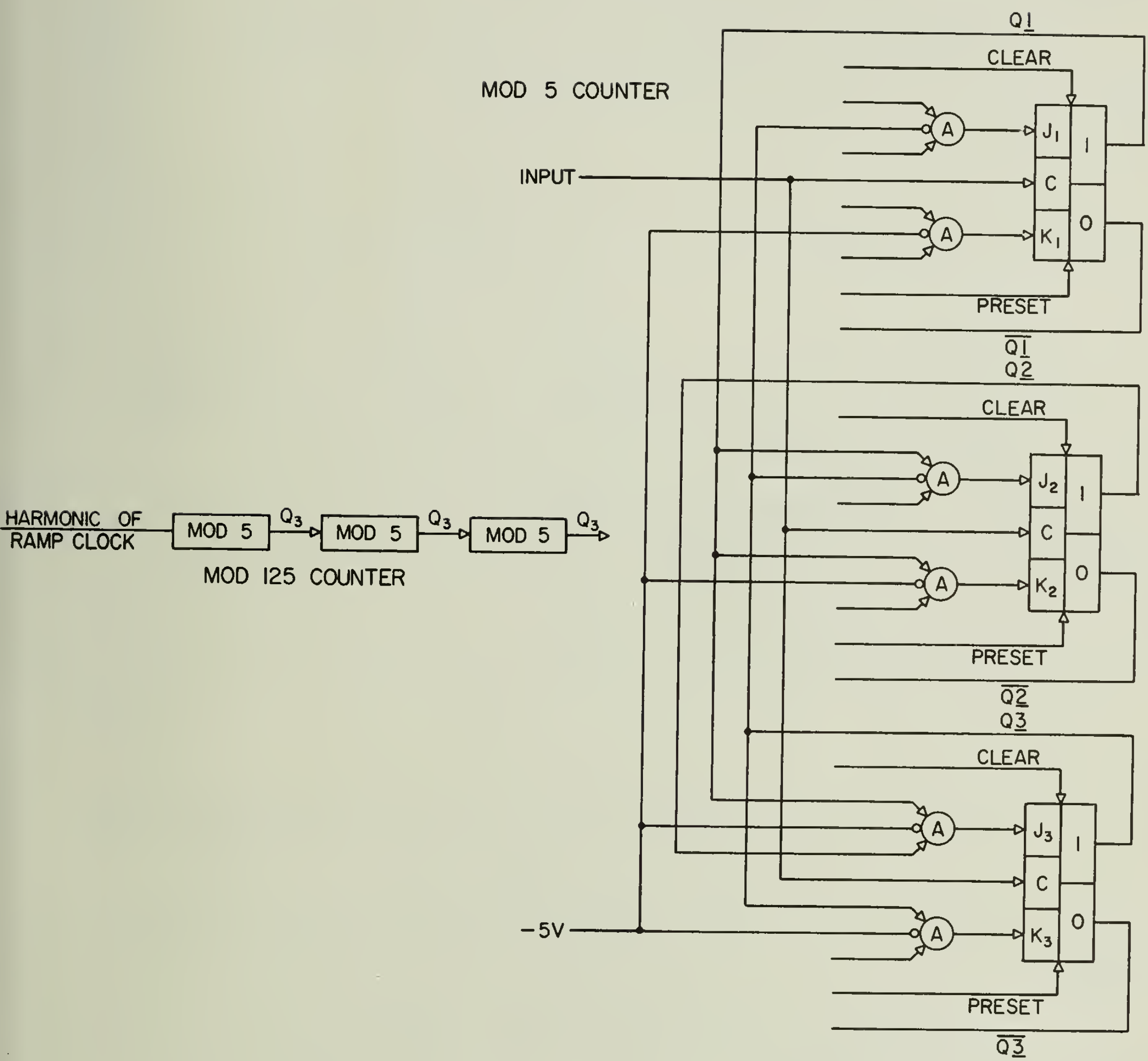


Figure 5. Modulo 5 Counter

The three states not used must lead to the sequence shown above or the counter will have to be preset when it is turned on. The three states not used are 011, 101, 111.

The table shown below shows that each of these three states leads to one of the states in the sequence used.

State at t_n			Input at t_{n+1}		
Q_1	Q_2	Q_3	J_1K_1	J_2K_2	J_3K_3
0	1	1	01	00	01
0	1	0			
1	0	1	01	01	01
0	0	0			
1	1	1	01	01	11
0	0	0			

Therefore no presetting of this counter is necessary since no matter what state it starts in it always goes to the correct sequence.

The signal Q_3 of the last stage is used to drive the ramp generator and the signal $\bar{Q}_3$ is used to drive the control circuit.

2.3 Ramp Generator and Analog-to-Phase Converter

The ramp generator circuit is shown in Figure 6. The circuit is of the bootstrap sweep circuit type. Transistor Q_1 is used

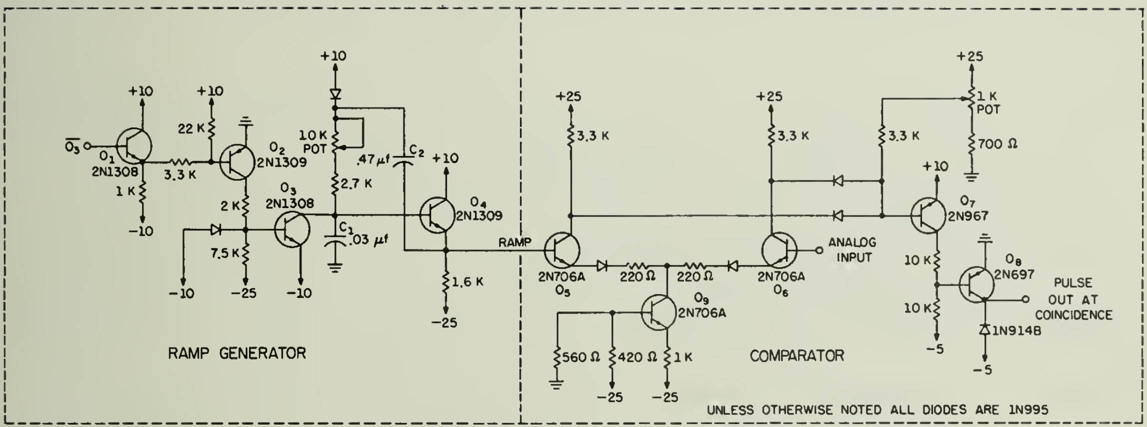


Figure 6. Ramp Generator and Amplitude-to-Phase Converter

as an emitter follower which turns Q_2 on when $\overline{Q}_3$ is at -5 volts and turns Q_2 off when $\overline{Q}_3$ is at ground potential. When Q_2 is turned off capacitor C1 charges and since Q_4 is an emitter follower the output ramp follows the charging of capacitor C1. The bootstrap capacitor C2 aids in giving a constant charging current to C1 and therefore the output ramp is linear. When Q_3 is turned on the charging current is diverted through Q_3 and capacitor C1 discharges through Q_3.

The comparator or amplitude-to-phase converter, as it is used in Phastor, is shown in Figure 6. The operation of this circuit is as follows: the transistor Q_9 draws a constant current from the differential amplifier consisting of Q_5 and Q_6. The base of Q_5 has the ramp signal applied to it and repeatedly rises from -10 volts to +10 volts. The base of Q_6 has the analog voltage which we wish to store connected to it. This voltage is in the range -10 volts to +10 volts. As the ramp begins to rise Q_6 is turned on and Q_5 is turned off.

All of the current in Q_9 comes from Q_6 and consequently Q_7 is turned on. As the ramp rises it eventually reaches a point where it is nearly equal to the analog input voltage on the base of Q_6. Now, the current in Q_9 is split between Q_5 and Q_6 and their collectors rise and turn Q_7 off. As the ramp voltage rises still further Q_6 turns off and Q_5 conducts all of the current required by Q_9 and again Q_7 is turned off. Therefore, there is a time during the ramp when Q_7 is turned off.

When Q_7 turns off Q_8 is turned on and an output pulse from -5 volts to ground is obtained. This pulse called WRITE in Section 1.0, is the pulse which is gated to the delay line analog (phase) storage cell. The width of this pulse is controlled by the one kilohm potentiometer which controls the sensitivity of the differential amplifier.

2.4 Control Circuit

Since the control circuit in Figure 7 consists mainly of flip-flops it can most easily be explained by first explaining how the flip-flop works. The circuit for this flip-flop is shown in Figure 8. When SET is held at ground potential and RESET is floating, transistor Q_1 is turned off and with Q_1 off, Q_2 is turned on. The transistor is driven to saturation so that the output swing will be -5 volts to 0 volts. Similarly if RESET is held at ground and SET is allowed to float, Q_1 will turn on and Q_2 will turn off.

Now, returning to the control circuit in Figure 7 all three flip-flops are reset by pressing the RESET button. The signal Q_3 is the output of the mod 125 counter and the zero to one transition, corresponding to the start of each ramp is not allowed to pass the AND gate since the other input to the AND is the OR of $\overline{C2}$ and $\overline{C3}$ which are both -5 volts i.e. a logical zero. When INITIATE STORE is pressed flip-flop Number 1 changes state and the zero to one

CONTROL CIRCUIT 1834-15-30

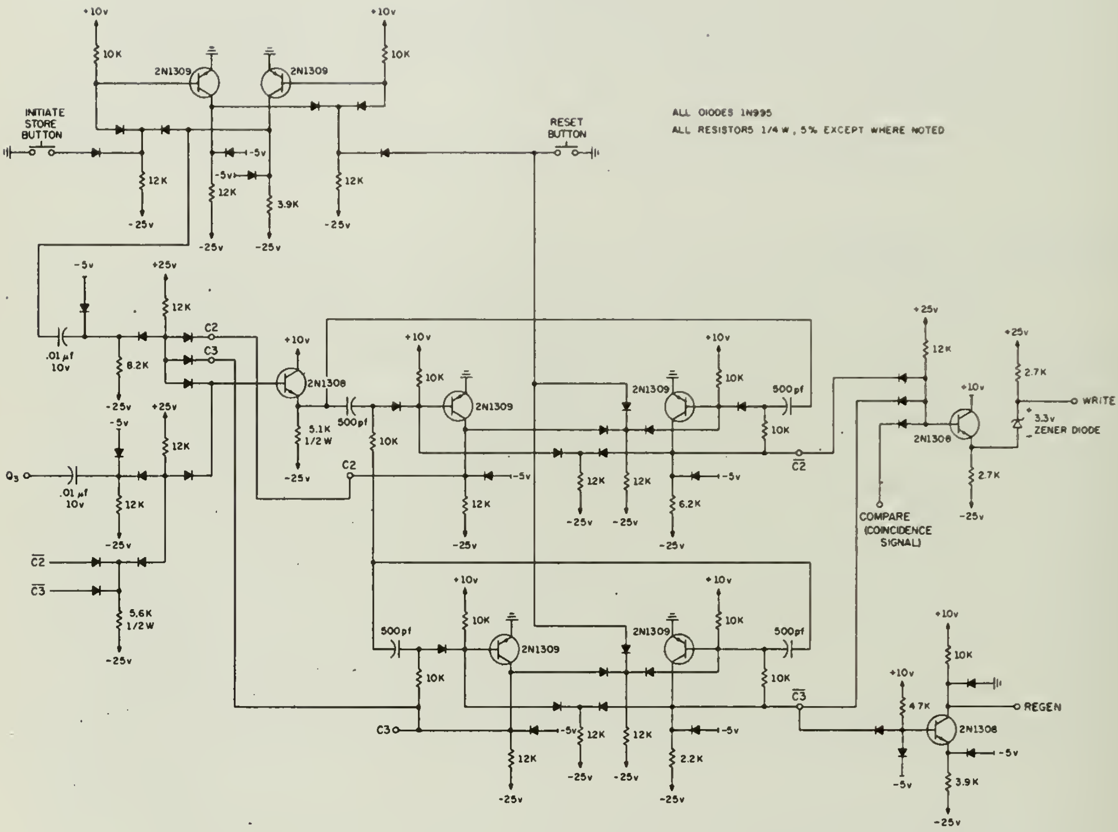


Figure 7. Control Circuit

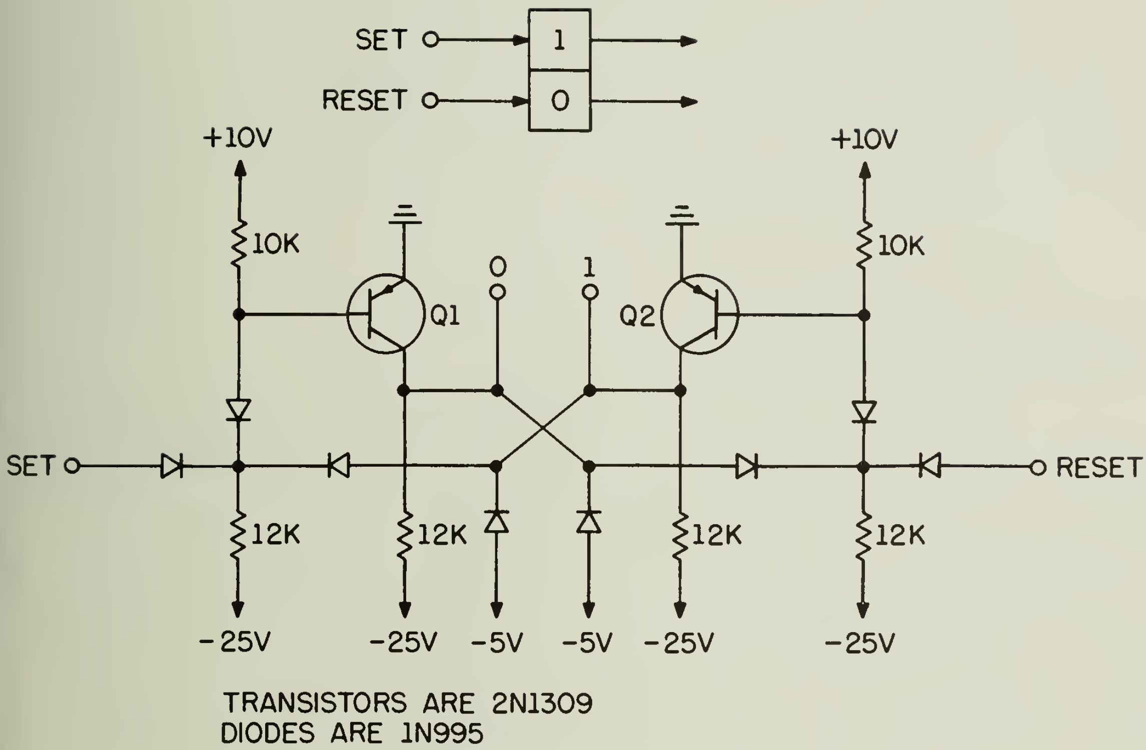


Figure 8. Flip-Flop

transition is allowed through the AND gate since C2 and C3 are both logical ones. This triggers flip-flop Number 2 which then starts the series of events discussed in the third paragraph of Section 2.

The level shifting circuit on the WRITE output is necessary since the delay line used needs a positive pulse for a trigger. The inverter on the REGEN output is used also as a level shifter and for current gain.

2.5 Storage Cell Delay Line

The circuit selected for use as the delay line is an emitter coupled monostable multivibrator with appropriately gated feedback which allows the delay line to regenerate the original input trigger and thereby to run continuously. This circuit is shown in Figure 10. The circuit shown in Figure 9 is the same monostable multivibrator without the feedback gating. This circuit operates in the following manner. The transistor Q_1 is normally off and Q_2 is normally on. When a positive trigger of sufficient amplitude and duration is applied to the base of Q_1, Q_1 is turned on. Now, the collector of Q_1 drops down to approximately zero volts, a jump of V_3 volts. This jump is transmitted unattenuated by capacitor C to the base of Q_2, and thus turns Q_2 off. Now, there are approximately $+V_3$ volts across capacitor C. With Q_1 on and Q_2 off capacitor C will eventually be charged to

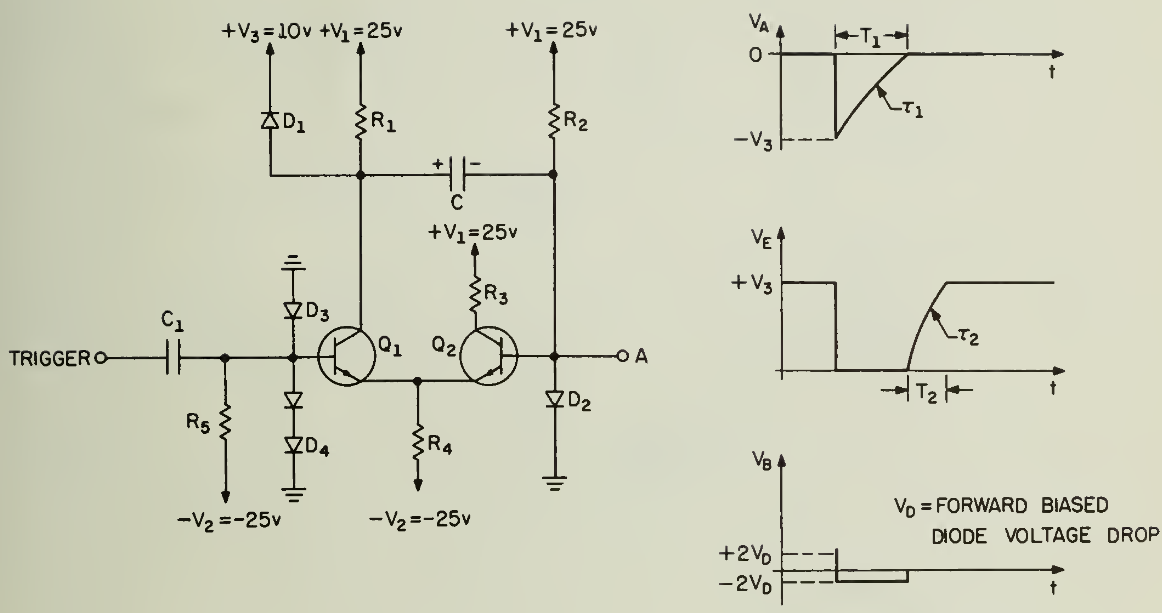


Figure 9. Emitter Coupled Monostable Multivibrator

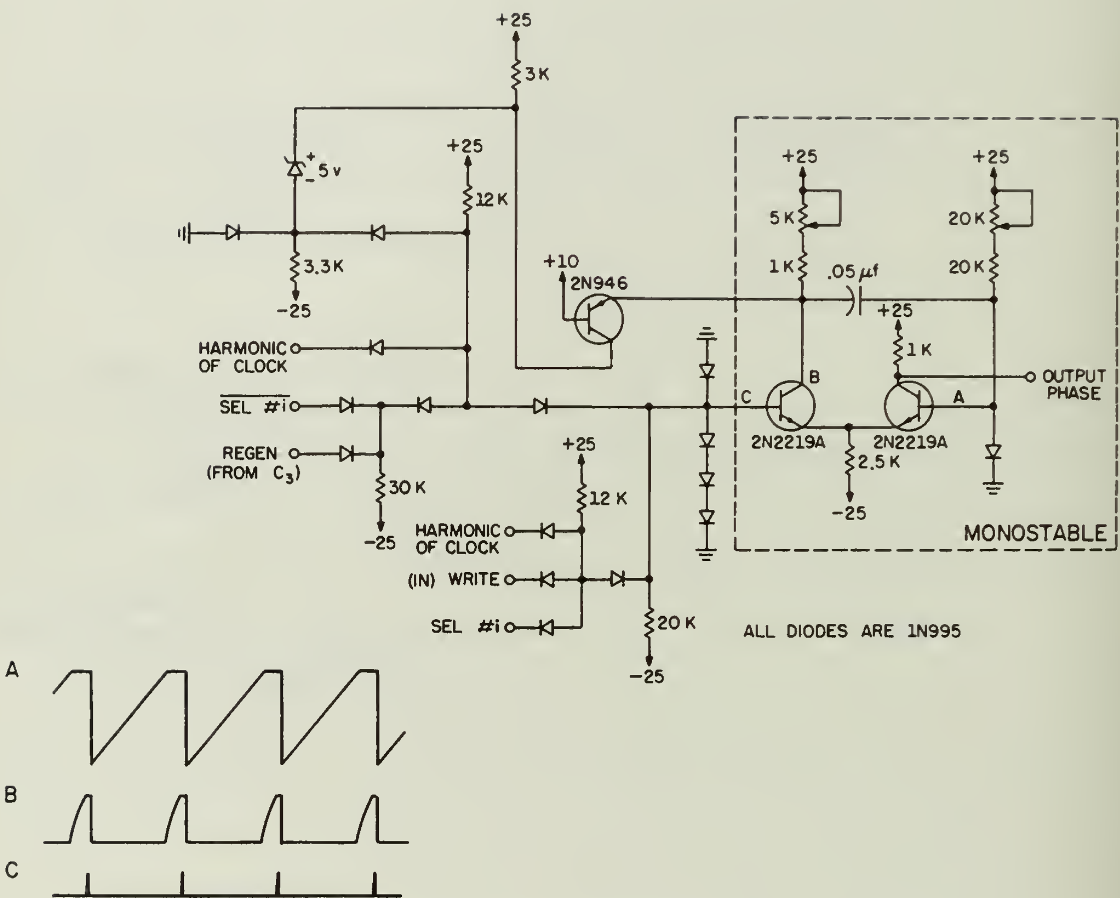


Figure 10. Storage Cell

$-V_1$ volts. So C starts to discharge through R_2 and the base of Q_2 rises. Q_1 is on so that the emitter of Q_2 is at approximately ground potential. When the base of Q_2 rises above ground, Q_2 is turned on and the emitter rises high enough to turn Q_1 off. The emitter waveform V_{B1} is shown in Figure 9. The collector of Q_1 is now free to rise, this is waveform V_E in Figure 9, as now C has approximately zero volts across it and with Q_1 off and Q_2 on apacitor C will eventually be charged to $+V_1$ volts. The collector of Q_1 rises toward $+V_1$ but it is caught at $+V_3$. The circuit is now in its stable state and may be retriggered.

The feedback necessary to make this circuit run as an astable multivibrator is obtained by replacing the diode D_1 by the base-emitter diode of a pnp transistor as shown in Figure 10. Now, when the collector of Q_1 rises near the end of the cycle, it eventually turns this added transistor on. The collector of this added transistor rises abruptly and thereby generates the positive trigger necessary to re-trigger the monostable and keep it running as an astable multivibrator. In Figure 10 the positive trigger occurs at the base of Q_1 when the harmonic of the clock pulse is present and gates the pulse to the base of transistor Q_1. In this way the period of the monostable multivibrator is quantized to an integral number of harmonic clock times. Therefore, the period of the monostable does not have to be adjusted exactly, but only within one harmonic clock period of the exact ramp clock period.

2.6 Calculation of the Period of the Emitter Coupled Monostable Multivibrator

The equations for the period of the emitter coupled monostable multivibrator can be calculated by referring to Figure 9.

When transistor Q_1 is on and Q_2 is off the current equation for point A is

$$C \frac{d\, V_A(t)}{dt} = \frac{V_1 - V_A(t)}{R_2}$$

Rewriting (1)

$$\frac{d\, V_A(t)}{dt} + \frac{V_A(t)}{R_2 C} = \frac{V_1}{R_2 C} \qquad (1)$$

To solve this equation the initial and final condition on V_A are needed. From previous discussion of the operation of this circuit it appears that $V_A(0) = -V_3$ volts and $V_A(\infty) = +V_1$ volts. Therefore solving equation (1) one has

$$V_A(t) = V_1 - (V_1 + V_3)\, e^{-t/\tau_1} \qquad (2)$$

where $\tau_1 = R_2 C$

Referring to Figure 9 it is seen that T_1 is the time required for the base of Q_2 to rise to zero volts, (i.e. $V_A(T_1) = 0$).

Now this equation can be solved for the time T_1.

From (2):

$$V_A(T_1) = V_1 - (V_1 + V_3)\, e^{-T_1/\tau_1} = 0$$

Therefore

$$T_1 = \tau_1 \ln \left(\frac{V_1 + V_3}{V_1}\right) \tag{3}$$

When transistor Q_1 is off and Q_2 is on the current equation at the collector of Q_1, call this point E, is as follows:

$$C \frac{d\, V_E(t)}{dt} = \frac{V_1 - V_E(t)}{R_1} \tag{4}$$

Rewriting (4)

$$\frac{d\, V_E(t)}{dt} + \frac{V_E(t)}{R_1 C} = \frac{V_1}{R_1 C} \tag{5}$$

To solve this equation there is needed the initial and final conditions on V_E. From the previous discussion of the operation of this circuit it follows that $V_E(0) = 0$ and $V_E(\infty) = +V_1$. Hence the solution of equation (5) is

$$V_E(t) = V_1(1 - e^{-t/\tau_2}) \tag{6}$$

where $\tau_2 = R_1C$

Referring to Figure 9 T_2 can be found as shown below.

$$V_E(T_2) = V_3 = V_1(1 - e^{-T_2/\tau_2})$$

Therefore,

$$T_2 = \tau_2 \ln(\frac{V_1}{V_1 - V_3}) \tag{7}$$

2.7 Calculation of the Circuit Parameters of the Emitter Coupled Monostable Multivibrator

Referring to the circuit shown in Figure 9 R_4 must be such that the current through it is not so large as to cause excessive power dissipation in the transistors. The voltage across R_4 is fairly constant as the emitter voltages of Q_1 and Q_2 do not vary very much. That is, they only vary one or two diode drops from

ground. If an emitter current I_E = 10ma is chosen, then

$$R_4 = \frac{25v}{10ma} = 2.5K$$

Transistors Q_1 and Q_2 are 2N2219A's which have a minimum β of 100. Therefore, in order to determine R_2, the base current required by Q_2 when it is one must be determined.

$$I_{B_2} = \frac{I_{E_2}}{\beta} = 0.1 \text{ ma}$$

The required I_{B_2} is 0.1 ma. It is also known that

$$I_{B_2} = \frac{25v}{R_2}$$

Therefore

$$0.1 \text{ ma} = \frac{25v}{R_2}$$

So

$$R_2 = 250K$$

Since Q_2 will not saturate, since the emitter current is fixed and the collector resistor can be chosen so that saturation does not occur, the resistor R_2 can be chosen smaller than 250K, since transistor Q_2 can be overdriven to be certain it gives a sharp signal at its collector. For an overdrive factor of about 7.5, R_2 can be chosen as R_2 = 33K.

To determine R_1, the transistor Q_1 must saturate so that the jump transmitted to Q_2 does not vary with the β of the particular transistor used. With Q_1 on and Q_2 off, I_{E_1} = 10 ma. There applies

$$I_{E_1} = \frac{25v}{R_1} = 10 \text{ ma}$$

Therefore

$$R_1 = 2.5K$$

Choose R_1 = 3K since additional current must come from base of Q_1 if R_1 cannot supply enough and therefore R_1 must nearly equal R_2 since a large base current in Q_1 is not desirable.

R_3 is chosen so that Q_2 does not saturate. A 10 volt drop in R_3 when Q_2 is on would be desirable as this will give a strong signal with which to operate the SAMPLE AND HOLD circuit. This collector (Q_2's) is used as the output point since it has almost no effect on the timing of the circuit and any loading at this point will therefore not effect the timing cycle of the monostable.

So

$$10v = I_{C_2} R_3$$

When Q_2 is on $I_{E_2} = 10$ ma. Since $I_{E_2} \approx I_{C_2}$

$$10v = R_3 I_{E_2} = R_3(10 \text{ ma})$$

$$R_3 = 1K$$

Now, to determine the value for capacitor C, the period of the RAMP CLOCK must be known since the monostable multivibrator must have the same period as the RAMP CLOCK. The frequency of the harmonic of the clock is 330 KHz and therefore the period of the RAMP CLOCK is

$$T_{rc} = 12.5 \cdot \frac{1}{330 \text{ KHz}} = 0.38 \text{ msec.}$$

$$T_{rc} = 380\ \mu\text{sec}$$

In Figure 9, the period of the monostable multivibrator is equal to T_1 plus T_2 where

$$T_1 = \tau_1 \ \ln \left(\frac{V_1 + V_3}{V_1}\right)$$

$$= R_2 C \ \ln \left(\frac{V_1 + V_3}{V_1}\right)$$

$$T_1 = C(33K) \ \ln (1.4)$$

and

$$T_2 = \tau_2 \ \ln \left(\frac{V_1}{V_1 - V_3}\right)$$

$$= R_1 C \ \ln \left(\frac{V_1}{V_1 - V_3}\right)$$

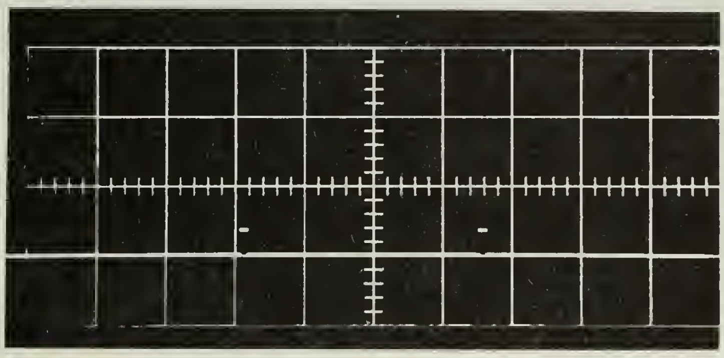
$$T_2 = C(3K) \ \ln \ (1.67)$$

then

$$T_{RC} = T_1 + T_2 = C(33K) \ \ln(1.4) + C(3K) \ \ln(1.67) = 380 \ \mu\text{sec}$$

$$C = 0.03 \ \mu\text{fd}$$

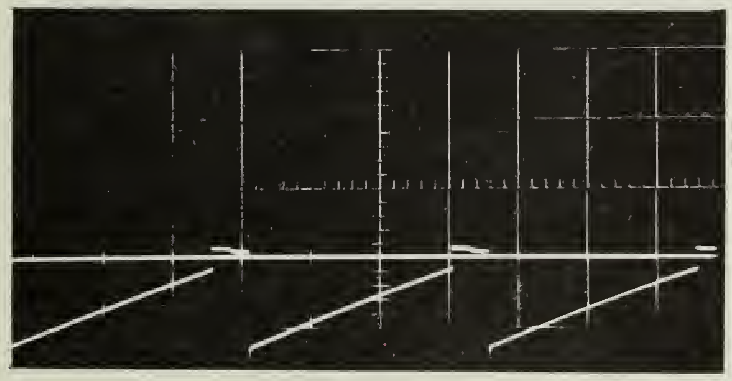
The waveforms obtained experimentally using the parameters determined in this section are shown in the oscillograms Figure 11.



(a)

Ground

Trigger Waveform
Time base = 100μ sec/cm
Voltage Scale = 5 volts/cm

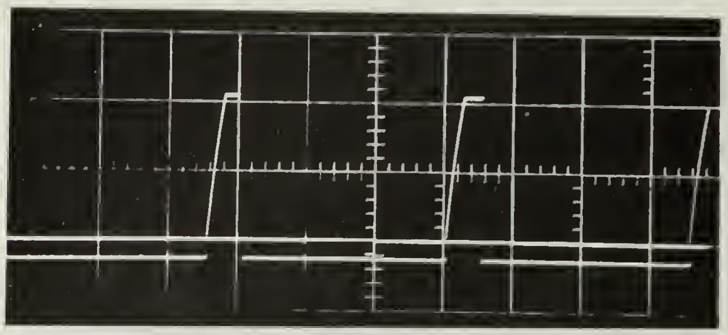


(b)

Ground

Waveform V_A
Time base = 100μ sec/cm
Voltage Scale = 5 volts/cm

Figure 11. Experimental Waveforms of the Emitter Coupled Monostable Multivibrator

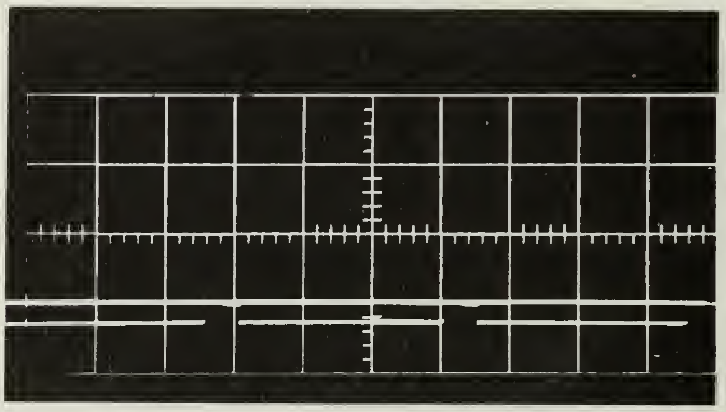


(c)

Ground

Waveform V_E

Time base = 100μ sec/cm
Voltage Scale = 5 volts/cm



(d)

Ground

Emitter Waveform

Time base = 100μ sec/cm
Voltage Scale = 5 volts/cm

Figure 11. Experimental Waveforms of the Emitter Coupled Monostable Multivibrator

2.8 Theoretical Calculation of Change of Period of Emitter-Coupled Monostable Corresponding to Small Variations of Supply Voltages

The supply voltages in the circuit of Figure 9 determine the total period of the monostable as can be seen by examining the equations for the periods.

$$T_1 = \tau_1 \ln \left(\frac{V_1+V_3}{V_1}\right)$$

$$T_2 = \tau_2 \ln \left(\frac{V_1}{V_1-V_3}\right)$$

Obviously, the period only depends to the first order on the supply voltages, V_1 and V_3. V_2 does not appear in these equations and therefore does not effect the period.

It is known that $V_1 = 25v$ and $V_3 = 10v$. Knowing the change in V_1 or V_3 the corresponding change in T_1 and T_2 can be calculated.

Thus, if V_1 is changed by +5%

$$T_1 + x_1\%T_1 = \tau_1 \ln\left(\frac{V_1+5\%V_1+V_3}{V_1+5\%V_1}\right)$$

and

$$T_2 + x_2\%T_2 = \tau_2 \ln\left(\frac{V_1+5\%V_1}{V_1+5\%V_1+V_3}\right)$$

Therefore, for V_1+5%V_1

$$T_1 + x_1\%T_1 = 0.322\ \tau_1 \text{ sec}$$

and

$$T_2 + x_2\%T_2 = .482\ \tau_1 \text{ sec}$$

for nominal values of V_1 and V_3 (i.e. V_1 = 25v, V_3 = 10v)

$$T_1 = 0.336\ \tau_1$$

and

$$T_2 = 0.506\ \tau_2$$

Then

$$\frac{T_1 + x_1\%T_2}{T_1} = \frac{0.322\ \tau_1}{0.336\ \tau_1}$$

$$x_1\% = -4\% \qquad (V_1 + 5\%V_1)$$

and

$$\frac{T_2 + x_2\%T_2}{T_2} = \frac{0.482\ \tau_2}{0.506\ \tau_2}$$

$$x_2\% = -5\% \qquad (V_1 + 5\%V_1)$$

Therefore, a 5% increase in V_1, results in 4% decrease in T_1 and a 5% decrease in T_2.

Also, for $V_1 - 5\%V_1$

$$T_1 - y_1\%T_1 = \tau_1 \ln \left(\frac{V_1 - 5\%V_1 + V_3}{V_1 - 5\%V_1}\right)$$

$$T_1 - y_1\%T_1 = 0.350\ \tau_1$$

and

$$T_2 - y_2\%T_2 = \tau_2 \ln \left(\frac{V_1 - 5\%V_1}{V_1 - 5\%V_1 - V_3}\right)$$

$$T_2 - y_2\%T_2 = 0.554\ \tau_2$$

Now

$$\frac{T_1 - y_1\% T_1}{T_1} = \frac{0.350\ \tau_1}{0.336\ \tau_1}$$

$$y_1\% = -4\% \qquad (V_1 - 5\% V_1)$$

and

$$\frac{T_2 - y_2\% T_2}{T_2} = \frac{0.554\ \tau_2}{0.506\ \tau_2}$$

$$y_2\% = -10\% \qquad (V_1 - 5\% V_1)$$

Therefore, a reduction of V_1 by 5% should result in a 4% increase in T_1 and a 10% increase in T_2.

Similarly, $\pm 5\%$ changes in V_3 give:

$$T_1 + x_1\% T_1 = \tau_1 \ln \left(\frac{V_1 + V_3 + 5\% V_3}{V_1}\right)$$

$$T_1 + x_1\% T_1 = .350\ \tau_1$$

and

$$T_2 + x_2\%T_2 = \tau_2 \ln \left(\frac{V_1}{V_1-(V_3+5\%V_3)}\right)$$

$$T_2 + x_2\%T_2 = 0.542\,\tau_2$$

Then

$$\frac{T_1 + x_1\%T_1}{T_1} = \frac{.350\ \tau_1}{.336\ \tau_1}$$

$$x_1\% = 4\% \qquad (V_3 + 5\%V_3)$$

and

$$\frac{T_2 + x_2\%T_2}{T_2} = \frac{.542\ \tau_2}{.506\ \tau_2}$$

$$x_2\% = 7\% \qquad (V_3 + 5\%V_3)$$

Therefore, an increase of 5% in V_3, results in an increase of 4% in T_1 and 7% in T_2.

Also

$$T_1 - y_1\%T_1 = \tau_1 \ln \left(\frac{V_1 + V_3 - 5\%V_3}{V_1}\right)$$

$$T_1 - y_1\%T_1 = .322\,\tau_1$$

and

$$T_2 - y_2\%T_2 = \tau_1 \ln \left(\frac{V_1}{V_1 - (V_3 - 5\%V_3)}\right)$$

$$T_2 - y_2\%T_2 = .476\,\tau_2$$

Then

$$\frac{T_1 - y_1\%T_1}{T_1} = \frac{.322\,\tau_1}{.336\,\tau_1}$$

$$y_1\% = 4\% \qquad (V_3 - 5\%V_3)$$

and

$$\frac{T_2 - y_2\%T_2}{T_2} = \frac{0.476\,\tau_2}{0.506\,\tau_2}$$

$$y_2\% = 6\% \qquad (V_3 - 5\%V_3)$$

Therefore, a decrease of 5% in V_3, results in a decrease of 4% in T_1 and a decrease of 6% in T_2.

2.9 Calculation From Experimental Results of the Change of Period of the Emitter-Coupled Monostable Multivibrator Corresponding to Small Variations of Supply Voltages

Experiments were carried out wherein the supply voltages V_1, V_2, and V_3 were changed by $\pm$ 5% and the resulting change in period recorded. The results are given below.

V_1	T_1	T_2
+25.00	310 μs	26 μs
+26.25	295 μs	25 μs
23.75	329 μs	29 μs

From this

$$T_1 + x_1\% T_1 = 295\,\mu s$$

$$x_1\% = -4.5\%$$

This value for $x_1\%$ compares favorably with the calculated value of $x_1\%$ which was -4%.

Also

$$T_1 - y_1\%T_1 = 320\,\mu s$$

$$y_1\% = -3\%$$

This compares favorably with the theoretical calculated value of -4%.

For T_2,

$$T_2 = 26\,\mu s$$

$$T_2 + x_2\%T_2 = 25\,\mu s$$

$$x_2\% = -4\%$$

The theoretical value from Section 2.8 was -5%.

$$T_2 - y_2\%T_2 = 29\,\mu s$$

$$y_2\% = -11\%$$

The theoretical value from Section 2.8 was -10%.

The results for variation in V_2 are shown below.

V_2	T_1	T_2
-25.00	310 μs	26 μs
-26.25	310 μs	26 μs
-23.75	310 μs	26 μs

As seen from the results, the period of the monostable does not depend upon V_2 for small changes in V_2.

For small changes in V_3, the results are shown below.

V_3	T_1	T_2
10.0	310 μs	26 μs
+10.5	310 μs	28 μs
+ 9.5	310 μs	25 μs

From this

$$T_1 + x_1\% T_1 = 310\ \mu s$$

Therefore

$$x_1\% = 0\%$$

$$T_2 + x_2\%T_2 = 28\ \mu s$$

$$x_2\% = +7.7\%$$

The calculated theoretical value of $x_1\%$ was 4%, and for $x_2\%$ the theoretical value was +7%. T_1 did not change because transistor Q_2 breaks down and the total jump is not used to determine T_1 and therefore a change in the jump does not change T_1 as long as the jump is greater than the voltage at which the transistor breaks down.

Also for decrease in V_3

$$T_1 - y_1\%T_1 = 310\ \ s$$

$$y_1\% = 0$$

and

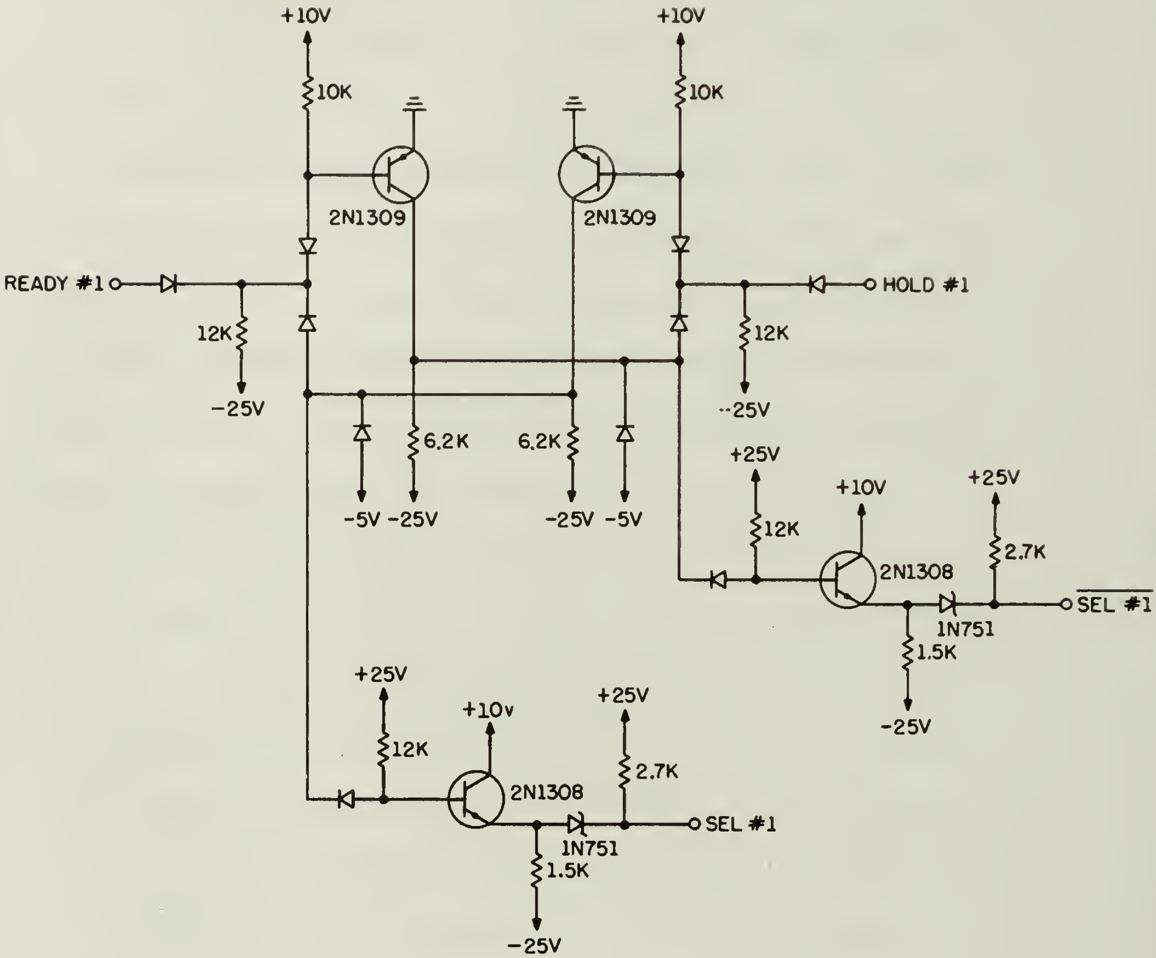
$$T_2 - y_2\%T_2 = 25\ \ s$$

$$y_2\% = 4\%$$

The theoretical values from Section 2.8 were 4% for $y_1\%$ and 6% for $y_2\%$.

2.10 Write Select Gate

The circuit shown in Figure 12 generates the signals which select the storage cell in which the analog voltage is to be stored. The circuit consists of a flip-flop which is similar to the flip-flop shown in Figure 8. The level shifters give the required positive gate to the analog storage cell. There is a double throw single pole switch connected to the flip-flop as shown in Figure 13. The pole of this switch is connected to ground and the normally closed contact is connected to the HOLD trigger diode on the flip-flop. The normally open contact is connected to READY on the flip-flop. In the model of Phastor which has been built there are four such switches with corresponding gating circuits, one for each of the storage cells. When the switch is in the normal position SEL is a logical zero and $\overline{\text{SEL}}$ is a logical one. This prevents any triggers from triggering the monostable storage cell and also prevents the information which may be stored in a cell from being erased when something is stored in another cell. These switches and their connections are shown in Figure 13 along with the readout switches. The switches used are Microswitch type push button double pole double throw. When one of WRITE (SELECT) switches is activated the analog input voltage is connected to the METER, so that the input can be monitored.



ALL DIODES ARE 1N995 EXCEPT AS NOTED.
1N751 IS SAME SIZE AS 1N995.
RESISTORS ARE 1/4 WATT, C.C., 5%.

Figure 12. Select Circuit

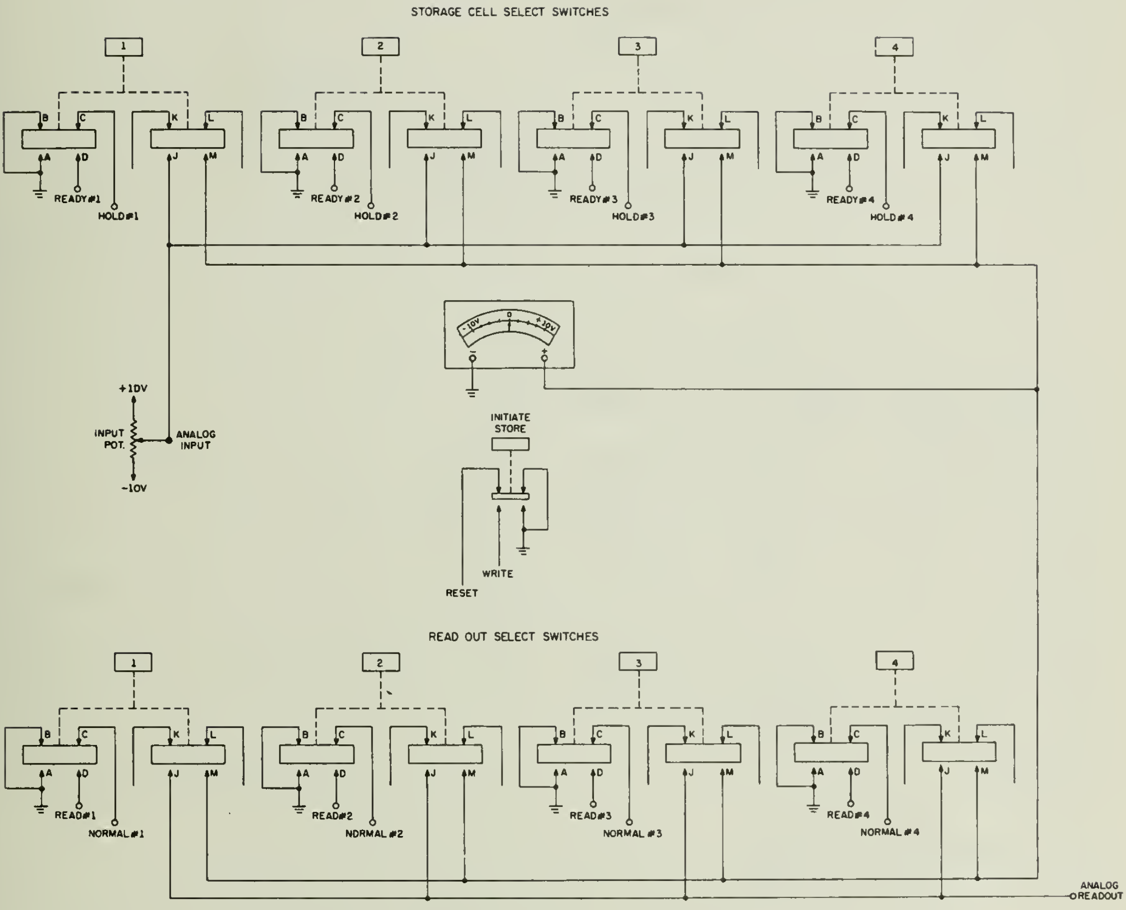


Figure 13. Push Button Connection Diagram

2.11 Readout Select Gate

The circuit used to generate the gate for the readout of the information stored in a cell is shown in Figure 14. The flip-flop is set and reset by one of the four READ switches in Figure 13. When the flip-flop is activated by setting the switch of the cell selected, the SAMP signal is allowed to trigger the SAMPLE and HOLD. The SAMP signal is the OUTPUT PHASE signal which comes from the collector of Q_2 in Figure 10 and is a 10 volt jump which occurs at the time at which the ramp is to be sampled. This jump is differentiated and the differentiated pulse is gated to an OR circuit whose output is connected to the SAMPLE and HOLD. The other inputs to this OR come from the three other cell readout select circuits. Therefore, when one of the READOUT switches is pushed a signal occurs at the output of the OR at the time corresponding to a voltage on the ramp. This voltage is the voltage which was originally stored in the cell.

2.12 Sample and Hold

The sample and hold circuit used in the system is shown in Figure 15. The circuit is essentially a flip-flop consisting of Q_1 and Q_2 and a switch Q_3 which allows a capacitor to be charged by the ramp clock until the stored pulse occurs. The counter output (start of ramp signal) sets the flip-flop, Q_1 and Q_2. Since a negative going pulse is needed to set the flip-flop the complement side of the

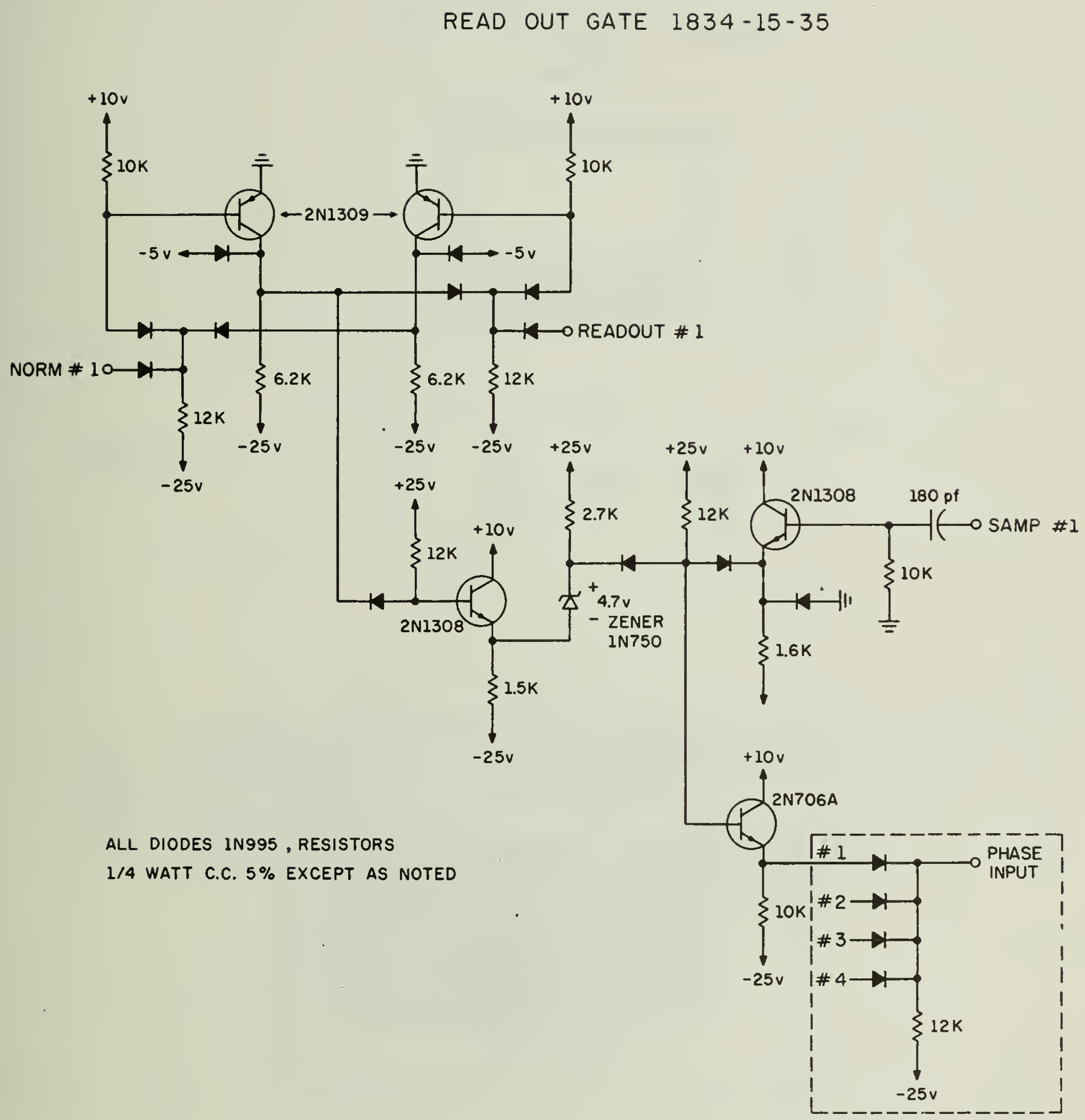


Figure 14. Readout Circuit

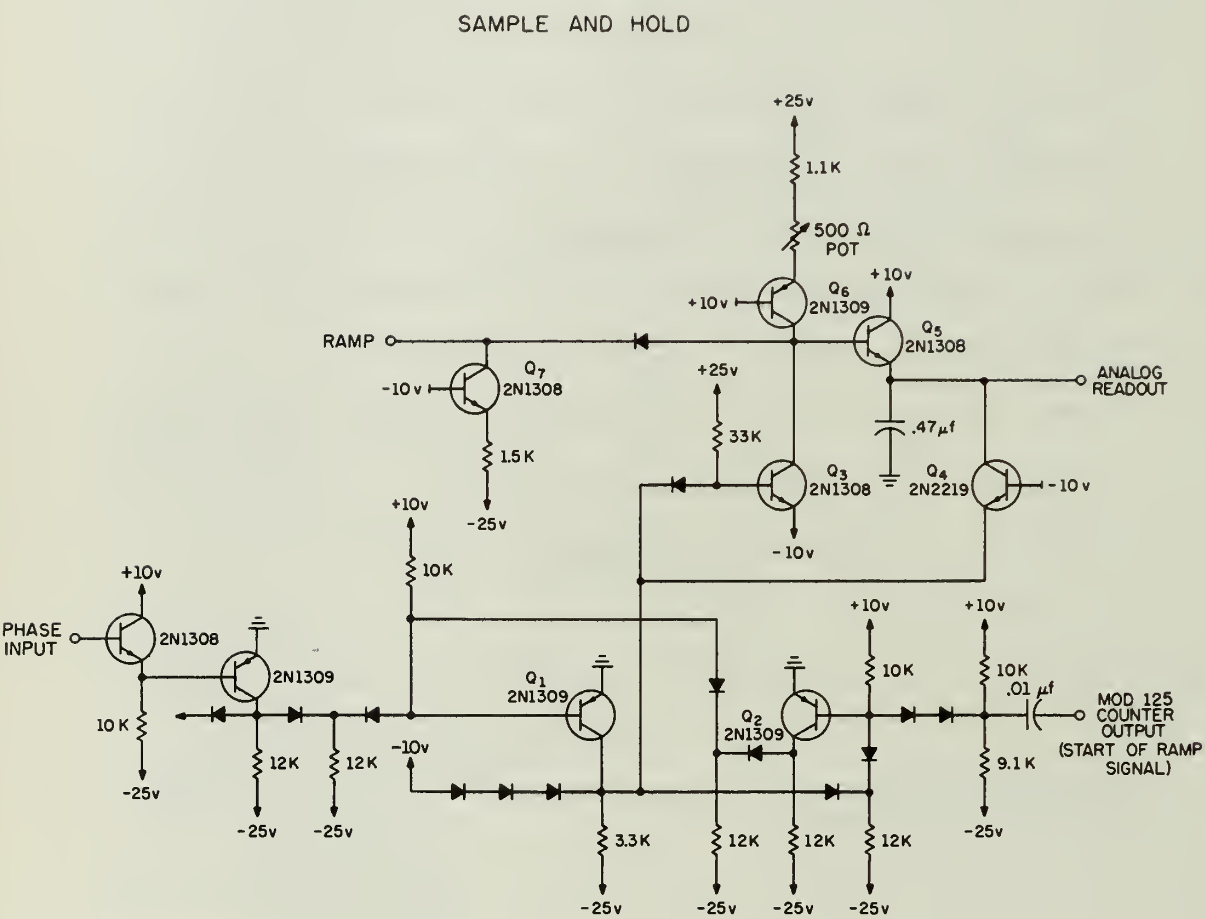


Figure 15. Sample-and-Hold Circuit

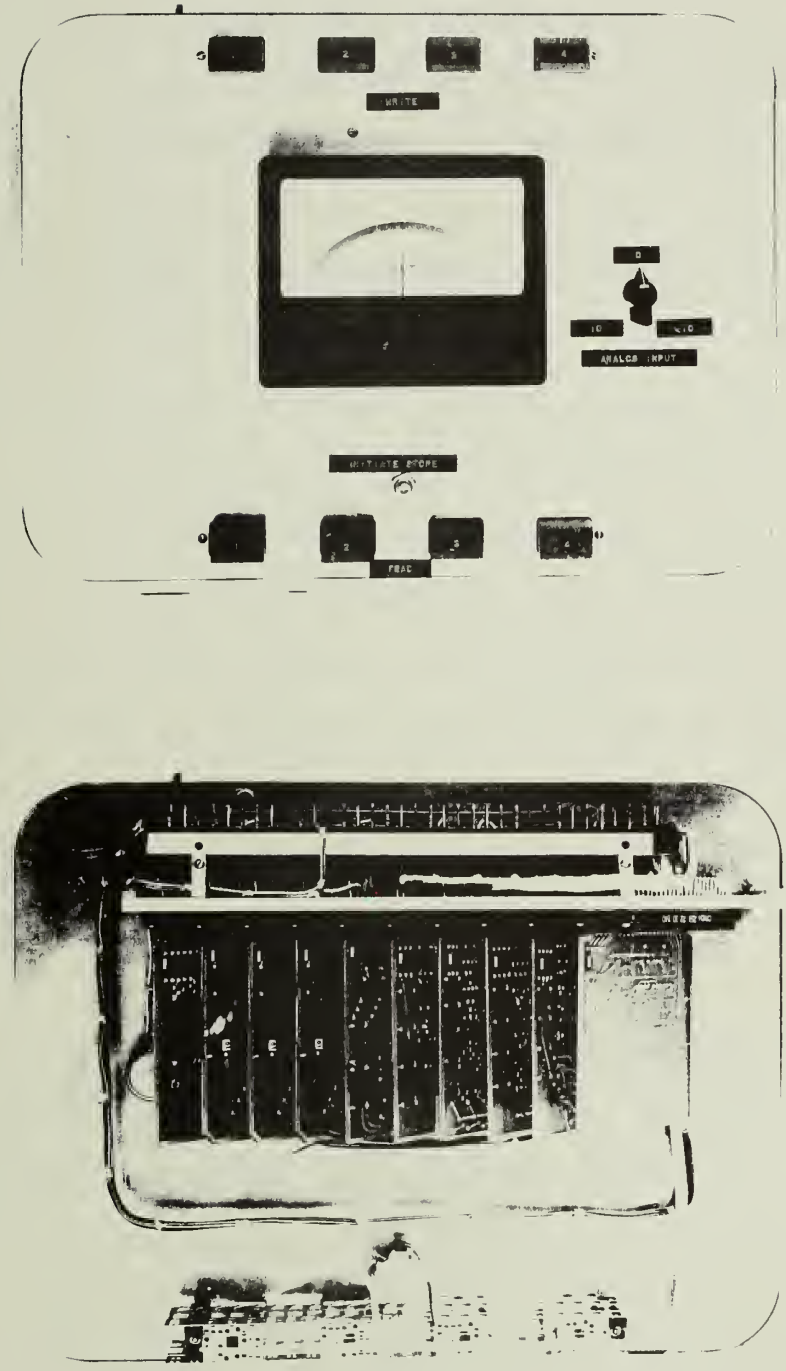


Figure 16. Panel Photographs

counter output is used. When the start of ramp signal occurs, Q_3 is turned off and allows the ramp to charge capacitor C, through transistor Q_5. Q_4 is turned on at the same time and provides a discharge path for C. When the PHASE INPUT signal from the READOUT GATE in Figure 14 resets the flip-flop the capacitor has been charged to the voltage which equals the voltage originally stored. Q_3 is turned on and Q_4 is turned off when the flip-flop is reset.

Q_5 is turned off by Q_3 turning on and therefore the capacitor can no longer be charged. The purpose of the current sources, Q_6 and Q_7, is to provide a constant current through the diode D_1 and provide a high impedance input point for the ramp signal. The potentiometer in the Q_6 emitter lead is used to balance the currents in Q_6 and Q_7. This balancing is accomplished by holding Q_3 off and Q_4 on and grounding the ramp input. Then the potentiometer is varied until the capacitor voltage is also at ground. Now the drop in the diode D_1 is equal to the base-emitter drop of Q_5.

2.13 Phastor Model and Description

The front panel of Phastor is shown in Figure 16. The system was built inside a carrying case and the only external connections are to the power supplies. The meter used is a Weston, 10-0-10, 20,000 ohm per volt taut band meter. The meter monitors both the analog input and the analog output depending upon which

button is pushed. If any one of the four SELECT buttons is pressed, the meter is connected to the input potentiometer and if any of the READ buttons is pressed the output of the SAMPLE and HOLD is connected to the meter. If none of the buttons is pressed, the meter connections float.

The back view of the panel shows the specially designed card rack which was necessary due to the limited depth of the carrying case.

3. OPERATION OF COLLECTOR - BASE COUPLED MONOSTABLE MULTIVIBRATOR

In sections 3 through 6, four circuits which could be used for the storage are discussed, analized and evaluated.

The collector-base coupled monostable multivibrator shown in Figure 17 is a second possibility for use as the storage element in the analog storage scheme. The operation of this multivibrator is as follows: the transistor Q_1 is normally off and Q_2 is normally on and saturated. Q_2 must be saturated in order to hold Q_1 off. A positive trigger will cause Q_1 to turn on and its collector will jump down to approximately ground potential. This jump is of magnitude V_2 since the collector of Q_1 was at V_2 before the trigger. The capacitor C transmits the jump of V_2 volts to the base of Q_2 and consequently Q_2 turns off. Now the collector of Q_2 is allowed to jump up and thus Q_1 is held on. Initially capacitor C had $+V_2$ volts across it. But now with Q_1 on, and Q_2 off, capacitor C will eventually charge to $-V_1$ volts, so the base of Q_2 starts to rise exponentially towards $+V_1$.

However, when the base of Q_2 rises above ground potential, Q_2 must turn on and as a result Q_1 turns off because the collector of Q_2 has now returned to ground. At this point capacitor C has zero volts across it but with Q_1 off and Q_2 on, capacitor C will eventually be charged to $+V_1$ volts so point C starts charging exponentially

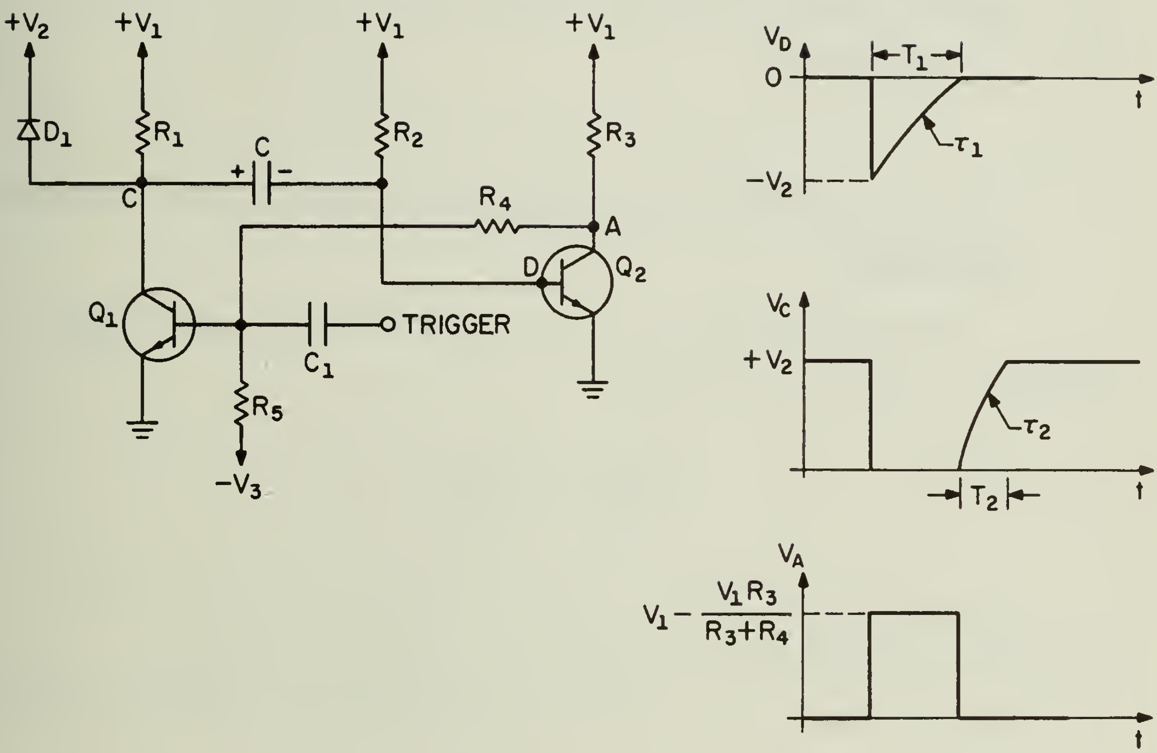


Figure 17. Collector-Base Coupled Monostable Multivibrator

towards $+V_1$. But when it rises above $+V_2$, D_1 turns on and the cycle is completed.

This monostable multivibrator may be converted to an astable with gated feedback by replacing D_1 by the base-emitter diode of a pnp transistor and gating the collector signal of this transistor back to the base of Q_1.

3.1 Calculation of the Period of the Collector-Base Coupled Monostable Multivibrator

Referring to Figure 17 with Q_1 on and Q_2 off, the current equation at point D is as follows:

$$C \frac{dV_D}{dt} = \frac{V_1 - V_D}{R_2}$$

Rewriting

$$\frac{dV_D}{dt} + \frac{V_D}{R_2 C} = V_1/R_2 C \qquad (1)$$

In order to effect a solution to equation (1) the initial and final values of V_D are needed. It is known from the discussion in Section 3.0 that $V_D(0) = -V_2$ and $V_D(\infty) = +V_1$. Therefore,

$$V_D(t) = V_1 - (V_1 + V_2)\, e^{-t/\tau_1}$$

where $\tau_1 = R_2C.$

Now referring to Figure 17, the solution for T_1, the time required for Q_2 to turn on is wanted. At this time $V_D(T_1) = 0.$ Then

$$V_D(T_1) = 0 = V_1 - (V_1 + V_2)\, e^{-T_1/\tau_1}$$

From this,

$$T_1 = \tau_1 \ln \left(\frac{V_1+V_2}{V_1}\right)$$

Again referring to Figure 17 with Q_1 off and Q_2 on, the current equation at point C is as follows:

$$C\,\frac{dV_C}{dt} = \frac{V_1-V_C}{R_1}$$

To effect a solution to this equation the initial and the final values of V_C are needed. From the discussion in Section 3.0 it is known that $V_C(0) = 0$ and $V_C(\infty) = +V_1$

Then

$$V_C(t) = V_1 - V_1 e^{-t/\tau_2}$$

where $\tau_2 = R_1 C$

Now the time period T_2 as indicated in Figure 17 can be solved for as follows: It is known that $V_C(T_2) = V_2$, so

$$V_C(T_2) = V_2 = V_1(1-e^{-T_2/\tau_2})$$

$$\therefore \quad T_2 = {}_2 \ln \left(\frac{V_1}{V_1 - V_2}\right)$$

3.2 Calculation of the Circuit Parameters of the Collector-Base Coupled Monostable Multivibrator

In Figure 17, when Q_2 is on Q_1 must be off, to guarantee this Q_2 should saturate.

To determine the collector and base resistors, R_3 and R_2, respectively, let

$$I_{R_3} = 5 \text{ ma}$$

Then

$$\frac{25}{R_3} = 5 \text{ ma}$$

$$R_3 = 5K$$

Set R_3 = 5.1K. To saturate Q_2, sufficient base current is needed, therefore, since

$$I_{B_2} = \frac{I_{C_2}}{\beta}$$

and since $I_{R_3} \approx I_{C_2}$ and β = 100 (minimum value for 2N2219A's) then

$$I_{B_2} = \frac{I_{C_2}}{\beta} = 0.05 \text{ ma}$$

Also $I_{B_2} = \frac{25v}{R_2}$

So

$$\frac{25v}{R_2} = 0.05 \text{ ma}$$

$$R_2 = 500K$$

This is a maximum value for R_2 and a smaller value will do. Set R_2 = 100K. Q_1 must also saturate, since the drop of collector Q_1 should be made independent of variations in β.

Let

$$I_{C_1} = 5 \text{ ma} = \frac{25v}{R_1}$$

From this

$$R_1 = 5K$$

Put

$$R_1 = 5.1K$$

$$I_{B_1} = \frac{I_{C_1}}{\beta} = 0.05 \text{ ma}$$

R_5 is the leakage current sink. Say, $I_{\text{Leakage}} = 10\,\mu a$

then

$$10 \text{ ma} = \frac{25v}{R_5}$$

$$R_5 = \frac{25v}{10 \times 10^{-3} \text{ ma}} = 2.5 \text{ megohm}$$

Put

$$R_5 = 1 \text{ meg}$$

Now when Q_1 is on

$$I_{B_{min}} = \frac{25v}{R_3 + R_{4\,max}} - 10\,\mu a = 0.05$$

$$R_{4max} = 500K$$

This is a maximum value of R_4, so choose

$$R_4 = 20K$$

To calculate C, the total period required of the monostable multivibrator must be known. Assume it to be the same as in the Phastor system, then

$$T_{TOTAL} = 380\,\mu s$$

From previous calculations it is known that

$$T_1 = R_2 C \ln \left(\frac{V_1+V_2}{V_1}\right)$$

$$T_2 = R_1 C \ln\left(\frac{V_1}{V_1 - V_2}\right)$$

$$T_1 + T_2 = T_{TOTAL}$$

$$T_{TOTAL} = C \left[R_2 \ln\left(\frac{V_1 + V_2}{V_1}\right) + R_1 \ln\left(\frac{V_1}{V_1 - V_2}\right)\right] = 380 \mu s$$

From this,

$$\underline{C = 0.015 \mu fd}$$

The waveforms obtained experimentally using the parameters determined in this section are shown in the oscillograms of Figure 18.

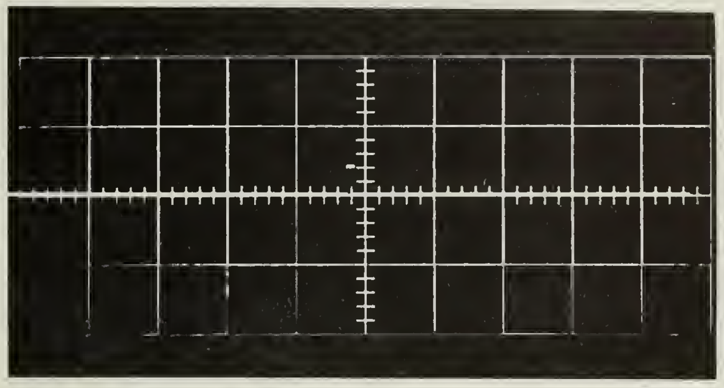
3.3 Theoretical Calculation of the Change of Period of the Collector-Base Coupled Monostable Corresponding to Small Variations of Supply Voltage

The equations from which the period of the collector-base coupled monostable of Figure 17 are determined are $T_1 = \tau_1 \ln\left(\frac{V_1 + V_2}{V_1}\right)$ and $T_2 = \tau_2 \ln\left(\frac{V_1}{V_1 - V_2}\right)$. The supply voltages used are +25 volts for V_1 and +10 volts for V_2. Now, knowing the corresponding change in the supply voltage the period can be calculated.

Thus, if V_1 is changed by +5%

$$T_1 + x_1\% T_1 = \tau_1 \ln\left(\frac{V_1 + 5\% V_1 + V_2}{V_1 + 5\% V_1}\right)$$

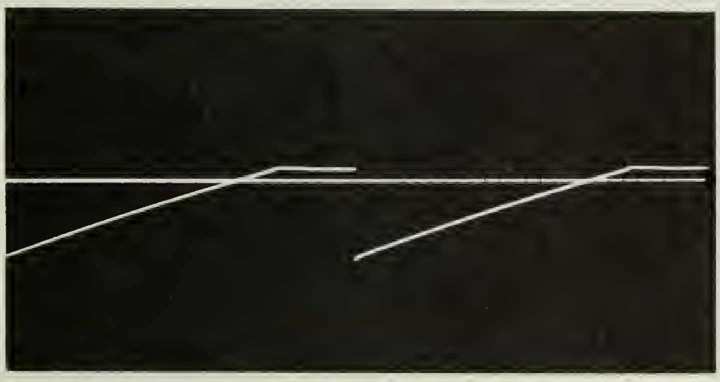
Ground



(a)

Trigger
Time Base = 100μsec/cm
Voltage Scale = 5 volts/cm

Ground

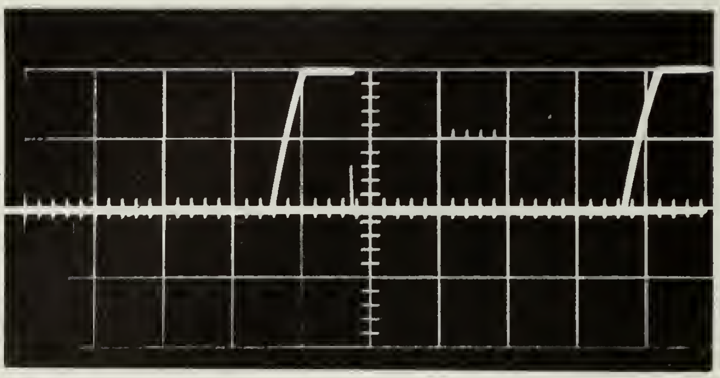


(b)

Waveform V_D
Time Base = 100μsec/cm
Voltage Scale = 5 volts/cm

Figure 18. Experimental Waveforms of Collector-Base Coupled Monostable Multivibrator

Ground

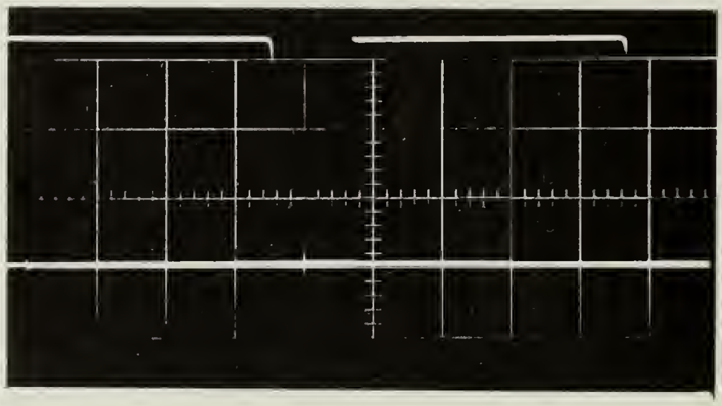


(c)

Waveform V_C

Time Base = 100μ sec/cm
Voltage Scale = 5 volts/cm

Ground



(d)

Waveform V_A

Time Base = 100μsec/cm
Voltage Scale = 5 volts/cm

Figure 18. Experimental Waveforms of Collector-Base Coupled Monostable Multivibrator

$$T_1 + x_1\%T_1 = 0.322\ \tau_1$$

Also for T_2

$$T_2 + x_2\%T_2 = \tau_2\ \ln(\frac{V_1+5\%V_1}{V_1+5\%V_1-V_2})$$

$$T_2 + x_2\%T_2 = 0.482\ \tau_2$$

Similarly, for V_1 decreased by 5%

$$T_1 -y_1\%T_1 = \tau_1\ \ln(\frac{V_1 5\%V_1+V_2}{V_1-5\%V_1})$$

$$T_1 - y_1\%T_1 = 0.350\ \tau_1$$

$$T_2 - y_2\%T_2 = \tau_2\ \ln(\frac{V_1-5\%V_1}{V_1-5\%V_1-V_2})$$

$$T_2 - y_2\%T_2 = 0.550\ \tau_2$$

For nominal values of V_1 and V_2 (i.e. V_1 = 25 volts and V_2 = 10 volts)

$$T_1 = \tau_1\ \ln(\frac{V_1+V_2}{V_1})$$

$$T_1 = 0.336\ \tau_1$$

$$T_2 = \tau_2\ \ln\left(\frac{V_1}{V_1 - V_2}\right)$$

$$T_2 = 0.512\ \tau_2$$

The percentage changes in T_1 and T_2 can now be solved for as follows:

$$\frac{T_1 + x_1\% T_1}{T_1} = \frac{0.322\ \tau_1}{0.336\ \tau_1}$$

$$x_1\% = -5\% \qquad (V_1 + 5\%\ V_1)$$

Therefore, a +5% change in V_1 corresponds to a -5% change in T_1.

$$\frac{T_2 + x_2\% T_2}{T_2} = \frac{0.482\ \tau_2}{0.512\ \tau_2}$$

$$x_2\% = -6\% \qquad (V_1 + 5\%\ V_1)$$

Therefore, a +5% change in V_1 corresponds to a -6% change in T_2.

Similarly, when V_1 is decreased by 5%

$$\frac{T_1 - y_1\%T_1}{T_1} = \frac{0.350\ \tau_1}{0.336\ \tau_1}$$

$$y_1\% = -2\% \qquad (V_1 - 5\%\ V_1)$$

Thus, a 5% decrease in V_1 corresponds to a 2% increase in T_1

$$\frac{T_2 - y_2\%T_2}{T_2} = \frac{0.550\ \tau_2}{0.512\ \tau_2}$$

$$y_2\% = -3.6\% \qquad (V_1 - 5\%\ V_1)$$

Thus, a 5% decrease in V_1 corresponds to a 3.6% increase in T_2.

Similar calculations can be done for variation in supply voltage V_2.

So, for a 5% increase in V_2

$$T_1 + x_1\%T_1 = \tau_1\ \ln\left(\frac{V_1+V_2+5\%V_2}{V_1}\right)$$

$$T_1 + x_1\%T_1 = 0.350\ \tau_1$$

$$T_2 + x_2\%T_2 = \tau_2\ \ln\left(\frac{V_1}{V_1-(V_2+5\%V_2)}\right)$$

$$T_2 + x_2\%T_2 = 0.542\ \tau_2$$

Also, for a 5% decrease in V_2

$$T_1 - y_1\%T_1 = \tau_1\ \ln\left(\frac{V_1+V_2-5\%V_2}{V_1}\right)$$

$$= 0.322\ \tau_1$$

$$T_2 - y_2\%T_2 = \tau_2\ \ln\left(\frac{V_1}{V_1-(V_2-5\%V_2)}\right)$$

$$T_2 - y_2\%T_2 = 0.476\ \tau_2$$

Now the percentage change in T_1 and T_2 for a $\pm 5\%$ change in V_2 can be calculated.

$$\frac{T_1 + x_1\%T_1}{T_1} = \frac{0.350\ \tau_1}{0.336\ \tau_1}$$

$$x_1\% = 2\% \qquad (V_2 + 5\%V_2)$$

So a 5% increase in V_2 corresponds to a 2% increase in T_1, and

$$\frac{T_2 + x_2\% T_2}{T_2} = \frac{0.542\ \tau_2}{0.512\ \tau_2}$$

$$x_2\% = 3\% \qquad (V_2 + 5\% V_2)$$

Therefore, a 5% increase in V_2 corresponds to a 3% increase in T_2.

For a 5% decrease in V_2 the corresponding change in T_1 and T_2 can also be calculated

$$\frac{T_1 - y_1\% T_1}{T_1} = \frac{0.322\ \tau_1}{0.336\ \tau_1}$$

$$y_1\% = 4.5\% \qquad (V_2 - 5\% V_2)$$

Therefore, a 5% decrease in V_2 corresponds to 4.5% decrease in T_1.

$$\frac{T_2 - y_2\% T_2}{T_2} = \frac{0.476\ \tau_2}{0.512\ \tau_2}$$

$$y_2 = 7\% \qquad (V_2 - 5\% V_2)$$

So, a 5% decrease in V_2 corresponds to a 7% decrease in T_2.

3.4 Calculation from Experimental Results of the Change of Period of the Collector-Base Coupled Monostable Corresponding to Small Variations of Supply Voltages

The collector base coupled monostable circuit shown in Figure 17 was tested by varying the three supply voltages and measuring the changes in the period of the monostable. The results of changing V_1 are shown below.

V_1	T_1	T_2
25.00	410 μs	47 μs
26.25	380 μs	42 μs
23.75	430 μs	50 μs

The percentage change in T_1 and T_2 can be calculated.

$$T_1 + x_1\%T_1 = 380\ \mu s$$

$$x_1\% = -7.5\% \qquad (V_1 + 5\%V_1)$$

The calculated theoretical value of $x_1\%$ is $x_1\% = -5\%$ from Section 3.3. Also,

$$T_2 + x_2\%T_2 = 42\ \mu s$$

$$x_2\% = 10.6\% \qquad (V_1 + 5\%V_1)$$

The calculated theoretical value of $x_2\%$ is $x_2\% = -6\%$ from Section 3.3. For the -5% change in V_1 the experimentally obtained value of y_1 and y_2 are found as follows:

$$T_1 - y_1\%T_1 = 430\,\mu s$$

$$y_1\% = -5\% \qquad (V_1 - 5\%V_1)$$

$$T_2 - y_2\%T_2 = 50\,\mu s$$

$$y_2\% = -6.5\% \quad (V_1 - 5\%V_1)$$

The calculated theoretical value of y_1 is -2% and of y_2 is -3.6% for a -5% change in V_1 from Section 3.3.

Similarly, for a +5% change in V_2

$$T_1 + x_1\%T_1 = 410\,\mu s$$

$$x_1\% = 0 \qquad (V_2 + 5\%V_2)$$

and

$$T_2 + x_2\% T_2 = 51\,\mu s$$

$$x_2\% = 8.2\% \qquad (V_2 + 5\% V_2)$$

The theoretical calculated value of $x_1\%$ is 2% and $x_2\%$ is 3%.

For a -5% change in V_2, $y_1\%$ and $y_2\%$ can also be calculated.

$$T_1 - y_1\% T_1 = 410\,\mu s$$

$$y_1\% = 0 \qquad (V_2 - 5\% V_2)$$

$$T_2 - y_2\% T_2 = 44\,\mu s$$

$$y_2\% = 6.4\% \qquad (V_2 - 5\% V_2)$$

The theoretical calculated values are $y_1\% = 4.5\%$ and $y_2\% = 7\%$.

4. OPERATION OF COMPLEMENTARY TRANSISTOR MONOSTABLE MULTIVIBRATOR

A third possibility for the multivibrator to be used in the analog storage scheme is the complementary transistor monostable multivibrator shown in Figure 19. The operation of this circuit is as follows: The Transistors Q_1 and Q_2 are normally biased on. The collector of Q_1 is the collector of Q_2. A negative trigger applied to the base of Q_1 turns it off. When Q_1 is turned off its collector is allowed to jump up to the voltage determined by the voltage divider R_1 and R_2 on V_1 and V_2. This jump is transmitted through capacitor C to the base of Q_2, turning Q_2 off. With Q_2 off its collector falls and keeps Q_1 off. Before the trigger, capacitor C had zero volts across it, but now with Q_1 and Q_2 off point A will eventually charge to $-V_2$ volts and point B will eventually charge to $-V_2$ volts, i.e. C will have $V_1 + V_2$ volts across it. As point A drops exponentially, point B rises exponentially. When point A falls below ground Q_2 turns on and its collector rises and Q_1 turns on. Now both Q_1 and Q_2 are on and capacitor C has nearly $+V_1$ volts on it. Hence, capacitor C discharges very rapidly through Q_1 and Q_2 back to zero volts, thus completing the cycle.

The diode D_1 could be replaced by the base emitter diode of an n-p-n transistor and then the collector signal of this transistor could be used to retrigger Q_1. In this way monostable would be modified to an astable multivibrator.

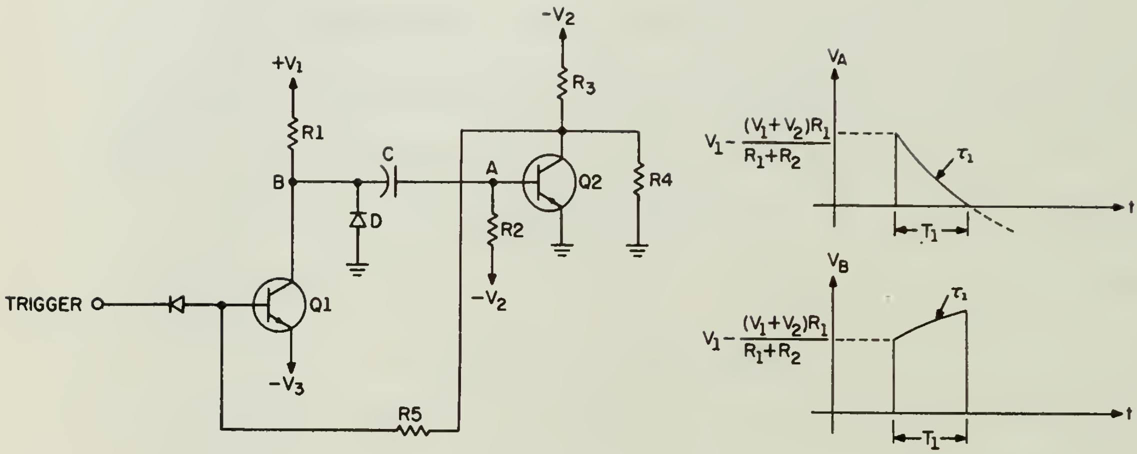


Figure 19. Complementary Transistor Monostable Multivibrator

4.1 Calculation of the Period of the Complementary Transistor Monostable Multivibrator

In the circuit of Figure 19 with Q_1 and Q_2 off the current equations at points A and B are as follows: At point A

$$C \frac{d(V_B - V_A)}{dt} = \frac{V_A - V_2}{R_2} \tag{1}$$

and at point B

$$C \frac{d(V_B - V_A)}{dt} = \frac{V_1 - V_B}{R_1} \tag{2}$$

From equations (1) and (2)

$$\frac{V_1 - V_B}{R_1} = \frac{V_A - V_2}{R_2} \tag{3}$$

Now solve equation (3) for V_B in terms of V_A, thus

$$V_B = V_1 - \frac{R_1}{R_2} (V_A - V_2) = V_1 + \frac{R_1}{R_2} (V_2 - V_A)$$

Substituting this into equation (1)

$$C \frac{d}{dt} (V_1 + \frac{R_1}{R_2} (V_2 - V_A) - V_A) = \frac{V_A - V_2}{R_2}$$

$$(R_1+R_2)\ C\ \frac{dV_A}{dt} = V_2 - V_A$$

$$\frac{dV_A}{dt} + \frac{V_A}{C(R_1+R_2)} = \frac{V_2}{(R_1+R_2)}$$

In order to solve this equation the initial and final conditions on V_A are needed. From Figure 19 and the discussion in Section 4.0 it is known that

$$V_A(0) = V_1 - \frac{(V_1+V_2)R_1}{R_1+R_2}$$

and

$$V_A(\infty) = -V_2$$

Hence

$$V_A(t) = (V_1+V_2 - \frac{(V_1+V_2)R_1}{R_1+R_2})\ e^{-t/\tau_1} - V_2$$

where $\tau_1 = C(R_1+R_2)$

Similarly

$$V_B(0) = \frac{(V_1+V_2)R_1}{R_1+R_2}$$

and

$$V_B(\infty) = +V_1$$

Therefore

$$V_B(t) = V_1 - \frac{(V_1+V_2)R_1}{R_1+R_2} e^{-t/\tau_1}$$

Referring again to Figure 19 it is seen that T_1 is the time necessary for Q_2 to be turned on again after the trigger. At this time $V_A(T_1) = 0$.

$$V_A(T_1) = 0 = (V_1+V_2 - \frac{(V_1+V_2)R_1}{R_1+R_2}) e^{-T_1/\tau_1} - V_2$$

$$T_1 = \tau_1 \ln (\frac{R_2(V_1+V_2)}{V_2(R_1+R_2)})$$

4.2 Calculation of the Circuit Parameters of the Complementary Transistor Monostable Multivibrator

Referring to Figure 19, with Q_1 and Q_2 on, there is wanted $V_A = 0$ and $V_C = 0$. Therefore one must find R_1. Assume supply voltages

$$V_1 = +25v$$

$$V_2 = 25v$$

$$V_3 = 10v$$

Set $I_{C_1} = 5$ ma

Then

$$I_{C_1} = 5 \text{ ma} = \frac{25v}{R_{1\,min}}$$

$$R_{1\,min} = 5k$$

Choose

$$R_1 = 6.8k$$

Transistors are Q_1: 2N2219A and Q_2: 2N1309.

For this collector current, the base current required is

$$I_{B_1} = \frac{I_{C_1}}{\beta} = \frac{5 \text{ ma}}{100} = .05 \text{ ma}$$

Since $V_A = 0$ $\quad R_5 = \frac{5\text{v}}{.05 \text{ ma}} = 100\text{K}$. This is a maximum value for R_5.

Select $R_5 = 27\text{k}$

To determine R_3, select $I_{C_2} = 5$ ma

then

$$R_3 = \frac{25\text{v}}{5 \text{ ma}} = 5\text{k}$$

Select $R_3 = 5.1\text{k}$

To determine R_2, the base current for Q_2 is determined as

$$I_{B_2} = \frac{I_{C_2}}{\beta} = \frac{5 \text{ ma}}{30} = \frac{1}{6} \text{ ma}$$

$$R_2 = \frac{25\text{v}}{I_{B_2}} = 150\text{k}$$

Set $R_2 = 100$ k

To determine R_4, the voltage V_A must be negative enough to turn Q_1 off when Q_2 is off. $\underline{V_A \text{ must be less than } -10\text{v.}}$

Set $V_A = -10$v, then R_4 is determined from

$$-10\text{v} = \frac{-25\text{v}}{R_3 + R_4} R_4$$

$$\underline{R_4 = 3.3\text{K}}$$

Since the total period of this monostable is essentially T_1

Set $T_1 = 380\,\mu$s.

From previous calculations in Section 4.1

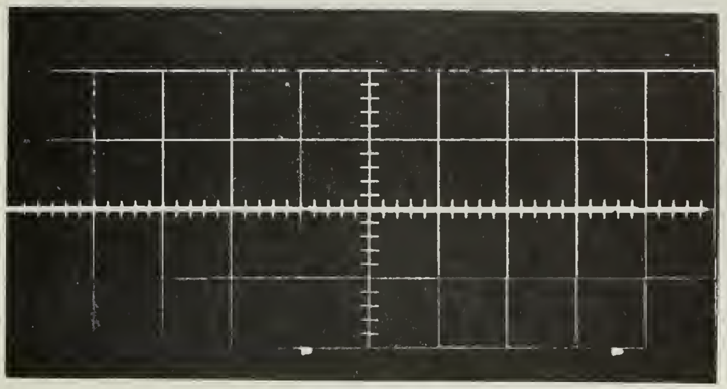
$$T_1 = R_2 C \ln \left(\frac{(V_1 + V_2)R_2}{(R_1 + R_2)V_2} \right)$$

From this

$$C = 0.00575\,\mu\text{fd}$$

$$\text{Set } C = 0.005\,\mu\text{fd}$$

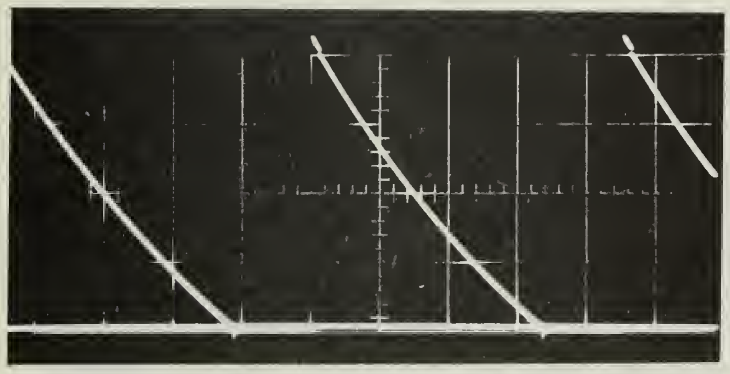
The waveforms obtained experimentally using the parameters determined in this section are shown in the oscillograms of Figure 20.



Ground

(a)

Trigger Waveform
Time Base = 100 μsec/cm
Voltage Scale = 5 volts/cm



Ground

(b)

Waveform V_A
Time Base = 100 μsec/cm
Voltage Scale = 5 volts/cm

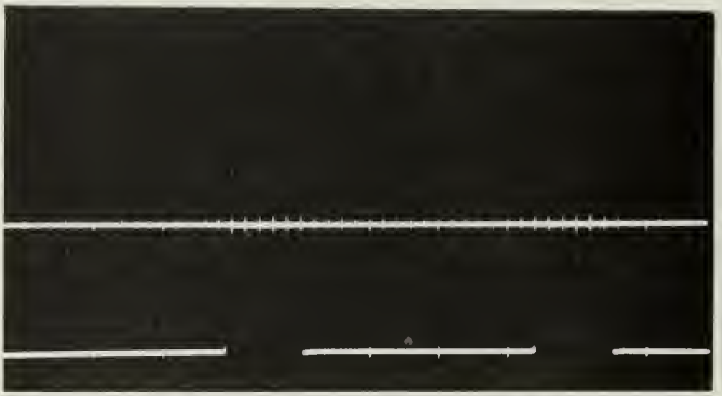
Figure 20. Experimental Waveforms of Complementary Transistor Monostable Multivibrator

(c)

Ground

Waveform V_B

Time Base = 100μsec/cm
Voltage Scale = 5 volts/cm



(d)

Ground

Waveform at Collector of Q_2

Time Base = 100μsec/cm
Voltage Scale = 5 volts/cm

Figure 20. Experimental Waveforms of Complementary Transistor Monostable Multivibrator

4.3 Theoretical Calculation of the Change of Period of the Complementary Transistor Monostable Corresponding to Small Variations of Supply Voltage

The equation from which the period of the complementary transistor monostable of Figure 19 is

$$T_1 = \tau_1 \ln\left(\frac{R_2(V_1+V_2)}{V_2(R_1+R_2)}\right)$$

where $\tau_1 = C(R_1+R_2)$, $R_1 = 6.8K$, $R_2 = 100K$

The supply voltages used are $V_1 = +25v$, $+V_2 = +25v$, and $V_3 = +10v$. The changes in the period T_1, corresponding to small changes in the supply voltage can be calculated.

Thus, if V_1 is increased by 5% the equation for T_1 becomes

$$T_1 + x_1\%T_1 = \tau_1 \ln\left(\frac{R_2(V_1+5\%V_1+V_2)}{V_2(R_1+R_2)}\right)$$

$$T_1 + x_1\%T_1 = .651\ \tau_1$$

Now also for no change in V_1 or V_2

$$T_1 = \tau_1 \ln\left(\frac{R_2(V_1+V_2)}{V_2(R_1+R_2)}\right)$$

$$T_1 = .627\ \tau_1$$

Therefore solving for $x_1\%$

$$\frac{T_1 + x_1\%T_1}{T_1} = \frac{.651\ \tau_1}{.627\ \tau_1}$$

$$x_1\% = 4\% \qquad (V_1+5\%V_1)$$

Similarly for V_1 decreased by 5%

$$T_1 - y_1\%T_1 = \tau_1 \ln \left(\frac{R_2(V_1-5\%V_1+V_2)}{V_2(R_1+R_2)}\right)$$

$$T_1 - y_1\%T_1 = 0.600\ \tau_1$$

Therefore solving for $y_1\%$

$$\frac{T_1 - y_1\%T_1}{T_1} = \frac{0.600\ \tau_1}{0.627\ \tau_1}$$

$$y_1\% = 4\% \qquad (V_1-5\%V_1)$$

Similar calculations can be done for variations in supply voltage V_2.

For an increase of 5% in V_2

$$T_1 + x_1\%T_1 = \tau_1 \ln \left(\frac{R_2(V_1+V_2+5\%V_2)}{(V_2+5\%V_2)(R_1+R_2)}\right)$$

$$T_1 + x_1\%T_1 = .604\ \tau_1$$

Now, solving for $x_1\%$

$$\frac{T_1 + x_1\%T_1}{T_1} = \frac{0.604\ \tau_1}{0.627\ \tau_1}$$

$$x_1\% = -3.5\% \qquad (V_2+5\%V_2)$$

For a decrease of 5% in V_2

$$T_1 - y_1\%T_1 = \tau_1 \ln \left(\frac{R_2(V_1+V_2-5\%V_2)}{(V_2-5\%V_2)(R_1+R_2)}\right)$$

$$T_1 - y_1\%T_1 = 0.651\ \tau_1$$

$$\frac{T_1 - y_1\%T_1}{T_1} = \frac{0.651\ \tau_1}{0.620\ \tau_1}$$

$$y_1\% = -5\% \qquad (V_2-5\%V_2)$$

According to these calculations a 5% increase or decrease in V_1 should result in a 4% increase or a 4% decrease respectively in T_1. Similarly a 5% increase or decrease in V_2 should result in a 3.5 decrease or a 5% increase respectively in T_1.

The supply voltage V_3 does not enter into the equation for T_1 and therefore for small changes in V_3 should not affect T_1.

4.4 Calculation from Experimental Results of the Change of Period of the Complementary Transistor Monostable Corresponding to Small Variations of Supply Voltages

In this section the results of experiments on the dependence of the period of the monostable on the supply voltage are summarized and compared with the theoretical results obtained in Section 4.3.

The experimental results obtained for variation in V_1 and V_2 are as follows:

V_1	T_1
25	350 μs
26.25	365 μs
23.75	335 μs

V_2	T_1
25	350 μs
26.25	340 μs
23.75	295 μs

$$T_1 = 350\,\mu\text{s}$$

$$T_1 + x_1\%T_1 = 365\mu s$$

$$x_1\% = 4\% \qquad (V_1+5\%V_1)$$

This compares well with the 4% value calculated in Section 4.3.

$$T_1 - y_1\%T_1 = 335\mu s$$

$$y_1\% = 4.2\% \qquad (V_1-5\%V_1)$$

This also compares well with the 4% value calculated in the previous section. Similarly, for a 5% increase in V_2 the equation is

$$T_1 + x_1\%T_1 = 340$$

$$x_1\% = -2.6\% \qquad (V_2+5\%V_2)$$

The value of -3.5% calculated in the previous section compares well with this value.

For a 5% decrease in V_2 the value of $y_1\%$ is calculated as follows:

$$T_1 - y_1\%T_1 = 295\,\mu s$$

$$y_1 = 15.5\% \qquad (V_2 - 5\%V_2)$$

5. OPERATION OF EMITTER COUPLED ASTABLE MULTIVIBRATOR

Another possibility for the storage element in the analog storage scheme is the astable multivibrator shown in Figure 21. This is an astable and could possibly be used without any modification as was necessary in the previous three circuits. The operation of this circuit is as follows. Assume Q_1 on and Q_2 off. Q_1 is not saturated. In this state point A will eventually charge to $+V_1$ volts, so the voltage increases at this point. When point A rises sufficiently high to turn Q_2 on, the charging current into capacitor C is diverted from C to Q_2. Consequently, the current in Q_1 decreases by this amount and allows the collector of Q_1 to fall lower since the collector current through resistor R_3 has been decreased. This action turns Q_2 on harder and the current in resistor R_2 increases and point A drops to approximately $+V_2$ volts. Point B follows this jump, as it takes place quite rapidly, and consequently, Q_1 is turned off. Now with Q_1 off and Q_2 on point B will eventually charge to $+V_1$ volts. Hence, it rises exponentially until it rises above $+V_3$ volts and turns Q_1 on. When Q_1 turns on its collector jumps up and turns Q_2 off. Now point A is at $+V_2$ volts and again rises towards $+V_1$ until it turns Q_2 on again, thus completing the cycle.

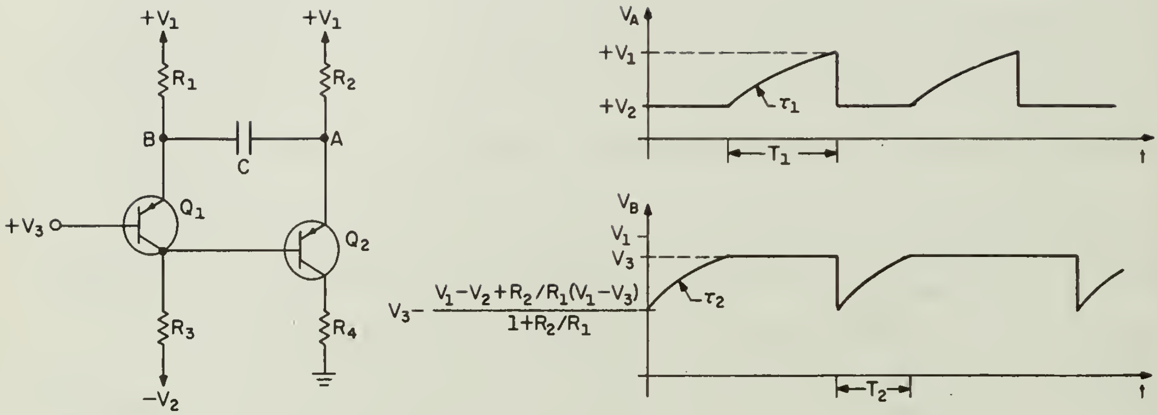


Figure 21. Emitter Coupled Astable Multivibrator

5.1 Calculation of the Period of the Emitter Coupled Astable Multivibrator

Assume Q_1 is on and Q_2 is off in the circuit of Figure 21. Then the current equation at point A is

$$C \frac{dV_A}{dt} = \frac{V_1 - V_A}{R_2}$$

Rewriting

$$\frac{dV_A}{dt} = \frac{V_A}{CR_2} = \frac{V_1}{CR_2}$$

To solve this equation the initial and final voltages at point A are needed. With Q_1 off and Q_2 on, $V_A(0) \approx +V_2$. Also it is known from the previous discussion that $V_A(\infty) = +V_1$. Therefore the solution for $V_A(t)$ is

$$V_A(t) = V_1 + (V_2 - V_1)\ e^{-t/\tau_1}$$

where

$$\tau_1 = R_2 C$$

In order to determine when Q_2 switches back on, the voltage at the collector of Q_1 must be known.

$$I_{E_1} = \frac{V_1 - V_B}{R_1} + \frac{V_1 - V_A}{R_2}$$

Then

$$V_B \approx V_3 \text{ and } V_A = V_1 - (V_1 - V_2)\, e^{-t/\tau_1}$$

From this

$$I_{E_1}(t) = \frac{V_1 - V_3}{R_1} + \frac{(V_1 - V_2)\, e^{-t/\tau_1}}{R_2}$$

Now since

$$I_{E_1} \approx I_{C_1}$$

$$V_{C_1} = V_2 + I_{C_1} R_3 \approx V_2 + I_{E_1} R_3$$

$$V_{C_1}(t) = V_2 + \frac{R_3}{R_1}(V_1 - V_3) + \frac{R_3}{R_2}(V_1 - V_2)^{-t/\tau_1}$$

Now Q_2 turns on when

$$V_A(T_1) = V_{C_1}(T_1)$$

and therefore have

$$V_1 - (V_1-V_2)\, e^{-T_1/\tau_1} = V_2 + \frac{R_3}{R_1}(V_1-V_3) + \frac{R_3}{R_2}(V_1-V_2)\, e^{-T_1/\tau_1}$$

From which

$$T_1 = \tau_1 \ln\left(\frac{1 + R_3/R_2}{1 - \frac{R_3}{R_1} \cdot \frac{(V_1-V_3)}{(V_1-V_3)}} \right)$$

Then solving for $V_{C_1}(T_1)$

$$V_{C_1}(T_1) = V_2 + \frac{V_1-V_2 + \frac{R_2}{R_1}(V_1-V_3)}{1 + R_2/R_3}$$

This voltage, $V_{C_1}(T_1)$, is the voltage at which Q_2 turns on. When Q_2 turns on, the charging current to capacitor C is diverted to Q_2 and therefore the current in Q_1 drops and consequently the voltage across R_3 drops and turns Q_2 on harder. The drop at C_1 also occurs at point A and is transmitted by capcitor C to point B and causes Q_1 to

turn off which causes V_{C_1} to drop further and turn Q_2 on more. Finally Q_1 will be off and Q_2 will be on and V_{C_1} will equal nearly $+V_2$ volts. The amount by which V_{C_1} drops is given by the second term of the last equation.

While Q_2 is on, the current equation at point B is

$$C \frac{dV_B}{dt} = \frac{V_1 - V_B}{R_1}$$

Rewriting

$$\frac{dV_B}{dt} + \frac{V_B}{R_1 C} = \frac{V_1}{R_1 C}$$

To solve this equation the initial and final conditions on V_B are needed. To find the initial voltage at V_B, go back to the state with Q_1 on and Q_2 off. $V_B = V_3$ before Q_1 turned off and the turn off jump is given by

$$V_o = \frac{V_1 - V_2 + {}^{R_2}/_{R_1} (V_1 - V_3)}{1 + {}^{R_2}/_{R_3}}$$

Hence

$$V_B(0) = V_3 - \frac{V_1 - V_2 + \frac{R_2}{R_1}(V_1 - V_3)}{1 + R_2/R_1}$$

The final voltage, $V_B(\infty)$, is easily seen to be $+V_1$.

Then the solution is

$$V_B(t) = V_1 + \left(V_3 - \frac{V_1 - V_2 + \frac{R_2}{R_1}(V_1 - V_3)}{1 + R_2/R_1} - V_1\right) e^{\frac{-(t-T_1)}{\tau_2}}$$

or

$$V_B(t) = V_1 + (V_3 - V_0 - V_1)\, e^{\frac{-(t-T_1)}{\tau_2}}$$

where

$$V_0 = \frac{V_1 - V_2 + \frac{R_2}{R_1}(V_1 - V_3)}{1 + R_2/R_1}$$

When $t = T_1 + T_2$ $\qquad V_B \approx V_3$

$$V_B(T_1 + T_2) = V_3 = V_1 + (V_3 - V_0 - V_1)\, e^{-T_2/\tau_2 = 1}$$

Which gives

$$T_2 = \tau_2 \ln \left(1 - \frac{V_0}{V_3 - V_1}\right)$$

5.2 Calculation of the Circuit Parameters of the Emitter Coupled Astable Multivibrator

Referring to Figure 21, when transistor Q_1 is on, it should not be saturated. Therefore,

$$V_{C_1} - 5 \text{ volt} < 10\text{v}$$

$$V_{C_1} < 15 \text{ volt}$$

Let

$$I_{E_1} = 5 \text{ ma}$$

Also

$$I_{E_1} = \frac{10\text{v}}{R_1} = 5 \text{ ma}$$

Set

$$\underline{R_1 = 2\text{K}}$$

Since $I_{E_1} \approx I_{C_1} = 5$ ma

Then

$$V_{C_1} = 5 + (5\text{ ma})(R_3) < 15\text{v}$$

$$R_3 < 2\text{K}$$

Set

$$R_3 = 1\text{K}$$

Now when Q_2 is on and Q_1 is off set $I_{E_2} = 5$ ma

Then

$$I_{E_2} = \frac{25-5}{R_2} = 5\text{ ma}$$

From this

$$R_2 = 4\text{K}$$

Set

$$\underline{R_2 = 4.3\text{K}}$$

V_{C_2} must be less than +5 volts and assume $I_{C_2} \approx I_{E_2}$

Therefore,

$$V_{C_2} = (5\ \text{ma})R_4 < 5\text{v}$$

$$R_4 < \frac{5\text{v}}{5\ \text{ma}} = 1\text{K}$$

Set

$$R_4 = 910\ \Omega$$

To determine C, set $T_{TOTAL} = T_1 + T_2 = 380\,\mu s$. From previous calculations

$$T_1 = R_2 C \ln \left(\frac{1 + {}^{R_3/R_2}}{1 - \frac{R_3}{R_1} \frac{(V_1 - V_3)}{(V_1 - V_2)}} \right)$$

From this

$$T_1 = C(4.3\text{K})(0.496)$$

And

$$T_2 = R_1C \ln \left(1 - \frac{V_0}{V_3 - V_1}\right)$$

Where

$$V_0 = \frac{V_1 - V_2 + \frac{R_2}{R_1}(V_1 - V_3)}{1 + R_2/R_1}$$

From this

$$T_2 = C(2K)(0.97)$$

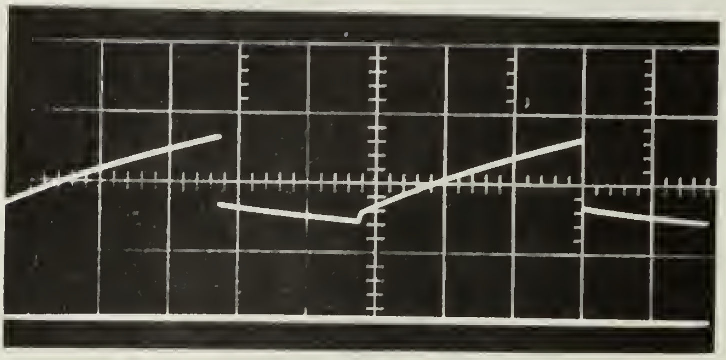
$$380\,\mu s = T_1 + T_2 = C(4.3K\ (.496) + (2K)\ \ln\ (0.97))$$

$$C = .0903\,\mu fd$$

Set

$$C = 0.1\,\mu fd$$

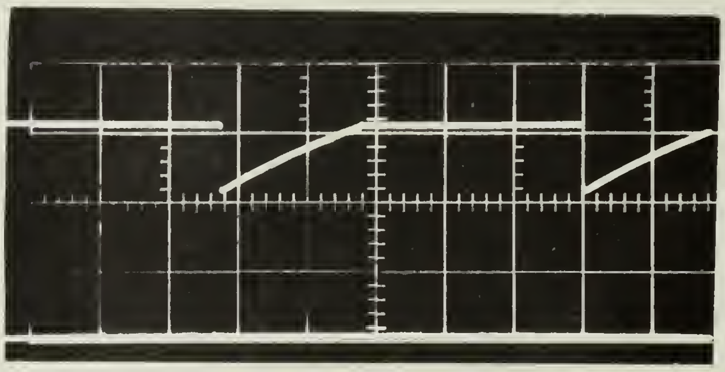
The waveforms obtained experimentally using the parameters determined in this section are shown in the oscillograms of Figure 22.



(a)

Waveform V_A

Time Base = 50μsec/cm
Voltage Scale = 5 volts/cm

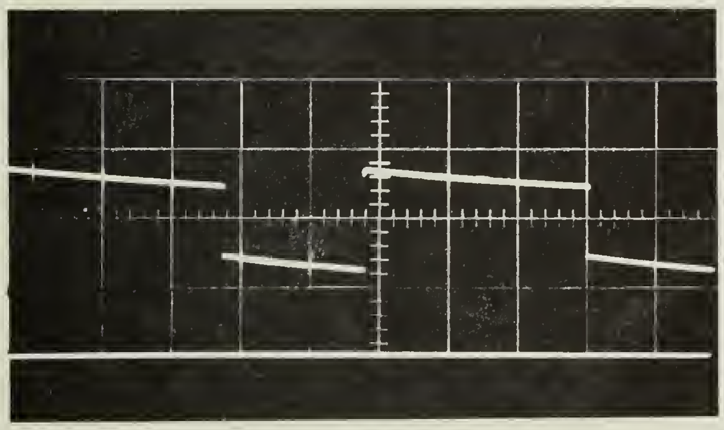


(b)

Waveform V_B

Time Base = 50μ sec/cm
Voltage Scale = 5 volts/cm

Figure 22. Experimental Waveforms of the Emitter Coupled Astable Multivibrator



(c)

Ground

Waveform at Collector of Q_1

Time Base = 50 μsec/cm

Voltage Scale = 5 volts/cm

Figure 22. Experimental Waveforms of the Emitter Coupled Astable Multivibrator

5.3 Theoretical Calculation of the Change of Period of the Emitter Coupled Astable Multivibrator Corresponding to Small Variations of Supply Voltages

The two equations for T_1 and T_2, the periods of the astable multivibrator (obtained in Section 5.1) are

$$T_1 = \tau_1 \ln \left(\frac{1 + {}^{R_3}/_{R_2}}{1 - \frac{R_3}{R_1} \frac{(V_1 - V_3)}{(V_1 - V_2)}} \right)$$

and

$$T_2 = \tau_2 \ln \left(1 - \frac{V_0}{V_3 - V_1}\right)$$

where

$$V_0 = \frac{R_1(V_1 - V_2) + R_2(V_1 - V_3)}{R_1 + R_2}$$

The values of the parameters in these two equations are the values calculated in Section 5.2.

They are

$R_1 = 2K$ $\qquad V_1 = 25v$

$R_2 = 4.3K$ $\qquad V_2 = 5v$

$R_3 = 1K$ $\qquad V_3 = 15v$

$R_4 = 910\ \Omega$

$C = 0.1\ \mu fd$

The nominal values of T_1 and T_2 are calculated using the above values.

$$T_1 = \tau_1 \ln \left(\frac{1 + {}^{R_3}/R_2}{1 - \frac{R_3}{R_1} \cdot \frac{V_1 - V_3}{V_1 - V_2}} \right)$$

$$T_1 = 0.496\ \tau_1$$

$$T_2 = \tau_2 \ln \left(1 - \frac{V_0}{V_3 - V_1}\right)$$

where

$$V_0 = \frac{R_1(V_1-V_2) + R_2(V_1-V_3)}{R_1+R_2}$$

Then

$$T_2 = 0.842\ \tau_2$$

The calculation of the values of T_1 and T_2 for variation in the power supplies V_1, V_2, and V_3 is carried out as shown below.

For V_1 increased by 5% the equation is

$$T_1 + x_1\%T_1 = \tau_1 \ln \left(\frac{1 + {}^{R_3}/R_2}{1 - \frac{R_3}{R_1} \cdot \frac{(V_1+5\%V_1-V_3)}{(V_1+5\%V_1-V_2)}} \right)$$

$$T_1 + x_1\%T_1 = .512\ \tau_1 \qquad (V_1+5\%V_1)$$

And for a 5% decrease in V_1

$$T_1 - y_1\%T_1 = \tau_1 \ln \left(\frac{1 + {}^{R_3}/R_2}{1 - \frac{R_3}{R_1} \cdot \frac{(V_1-5\%V_1-V_3)}{(V_1-5\%V_1-V_2)}} \right)$$

$$T_1 - y_1\%T_1 = 0.476\ \tau_1 \qquad (V_1 - 5\%V_1)$$

The theoretical values of $x_1\%$ and $y_1\%$ can now be determined. Thus

$$\frac{T_1 + x_1\%T_1}{T_1} = \frac{0.512\ \tau_1}{0.496\ \tau_1}$$

$$x_1\% = 3\% \qquad (V_1 + 5\%V_1)$$

and

$$\frac{T_1 - y_1\%T_1}{T_1} = \frac{0.476\ \tau_1}{0.496\ \tau_1}$$

$$y_1\% = 4\% \qquad (V_1 - 5\%V_1)$$

The changes in T_1 and T_2 for variations in V_2 are calculated as follows:

For a 5% increase in V_2

$$T_1 + x_1\%T_1 = \tau_1 \ln \left(\frac{1 + {}^{R_3}/R_2}{1 - \frac{R_3}{R_1} \left(\frac{V_1 - V_3}{V_1 - (V_2 + 5\%V_2)} \right)} \right)$$

$$T_1 + x_1\%T_1 = 0.500\ \tau_1 \qquad (V_2+5\%V_2)$$

And also for a 5% decrease in V_2

$$T_1 - y_1\%T_1 = \tau_1 \ln \left(\frac{1 + {}^{R_3}/R_2}{1 - \frac{R_3}{2} \left(\frac{V_1 - V_3}{V_1 - (V_2 - 5\%V_2)} \right)} \right)$$

$$T_1 - y_1\%T_1 = 0.490\ \tau_1 \qquad (V_2-5\%V_2)$$

The $x_1\%$ and $y_1\%$ for variation in V_2 can now be determined.

$$\frac{T_1 + x_1\%T_1}{T_1} = \frac{0.500\ \tau_1}{0.496\ \tau_1}$$

$$x_1\% = 1\% \qquad (V_2+5\%V_2)$$

$$\frac{T_1 - y_1\%T_1}{T_1} = \frac{0.490\ \tau_1}{0.496\ \tau_1}$$

$$y_1\% = 1\% \qquad (V_2-5\%V_2)$$

The values of $x_1\%$ and $y_1\%$ for variation in V_3 are calculated as follows:

$$T_1 + x_1\%T_1 = \tau_1 \ln \left(\frac{1 + {}^{R_3}/R_2}{1 - \frac{R_3}{R_1} \cdot \frac{V_1 - (V_3 + 5\%V_3)}{V_1 - V_2}} \right)$$

$$T_1 + x_1\%T_1 = 0.470\ \tau_1 \qquad (V_3 + 5\%V_3)$$

$$T_1 - y_1\%T_1 = \tau_1 \ln \left(\frac{1 + {}^{R_3}/R_2}{1 - \frac{R_3}{R_1} \cdot \frac{V_1 - (V_3 - 5\%V_3)}{V_1 - V_2}} \right)$$

$$T_1 - y_1\%T_1 = 0.525\ \tau_1 \qquad (V_3 - 5\%V_3)$$

Now $x_1\%$ and $y_1\%$ can be determined.

$$\frac{T_1 + x_1\%T_1}{T_1} = \frac{0.470\ \tau_1}{0.490\ \tau_1}$$

$$x_1\% = -5\% \qquad (V_3 + 5\%V_3)$$

and

$$\frac{T_1 - y_1\%T_1}{T_1} = \frac{0.525\ \tau_1}{0.496\ \tau_1}$$

$$y_1\% = -6\% \qquad (V_3 - 5\%V_3)$$

Similar calculations for T_2 may be carried out. For variation in V_1

$$T_2 + x_2\%T_2 = \tau_2 \ln\left(1 - \frac{V_0}{V_3 - (V_1 + 5\%V_1)}\right)$$

where

$$V_0 = \frac{R_1(V_1 + 5\%V_1 - V_2) + R_2(V_1 + 5\%V_1 - V_3)}{R_1 + R_2}$$

$$T_2 + x_2\%T_2 = 0.817\ \tau_2 \qquad (V_1 + 5\%V_1)$$

And for a 5% decrease in V_1

$$T_2 - y_2\%T_2 = \tau_2 \ln\left(1 - \frac{V_0}{V_3 - (V_1 - 5\%V_1)}\right)$$

$$V_0 = \frac{R_1(V_1-5\%V_1-V_2) + R_2(V_1-5\%V_1-V_3)}{R_1+R_2}$$

Then

$$T_2 - y_2\%T_2 = 0.845\ \tau_2 \qquad (V_1-5\%V_1)$$

$$\frac{T_2 + x_2\%T_2}{T_2} = \frac{0.817\ \tau_2}{0.842\ \tau_2}$$

$$x_2\% = -2\% \qquad (V_1+5\%V_1)$$

$$\frac{T_2 - y_2\%T_2}{T_2} = \frac{0.845\ \tau_2}{0.842\ \tau_2}$$

$$y_2\% = -0.5\% \qquad (V_1-5\%V_1)$$

For a 5% increase in V_2

$$T_2 + x_2\%T_2 = \tau_2 \ln\left(1 - \frac{V_0}{V_3-V_1}\right)$$

$$V_0 = \frac{R_1(V_1-(V_2+5\%V_2)) + R_2(V_1-V_3)}{R_1 + R_2}$$

$$T_2 + x_2\% T_2 = 0.842\ \tau_2 \qquad (V_2 + 5\% V_2)$$

For a 5% decrease in V_2

$$T_2 - y_2\% T_2 = \tau_2 \ln \left(1 - \frac{V_0}{V_3 - V_1}\right)$$

$$V_0 = \frac{R_1(V_1 - (V_2 - 5\% V_2)) + R_2(V_1 - V_3)}{R_1 + R_2}$$

$$T_2 - y_2\% T_2 = 0.841\ \tau_2 \qquad (V_2 - 5\% V_2)$$

The values of $x_2\%$ and $y_2\%$ for variation in V_2 can be calculated.

$$\frac{T_2 + x_2\% T_2}{T_2} = \frac{0.842\ \tau_2}{0.842\ \tau_2}$$

$$x_2\% = 0 \qquad (V_2 + 5\% V_2)$$

$$\frac{T_2 - y_2\% T_2}{T_2} = \frac{0.841\ \tau_2}{0.842\ \tau_2}$$

$$y_2\% = 0 \qquad (V_2 - 5\% V_2)$$

Thus, for small changes in V_2 the period T_2 does not change. Likewise similar calculations for the variation in T_2 corresponding to a variation in V_3 may be carried out.

For a 5% increase in V_3

$$T_2 + x_2\%T_2 = \tau_2 \ln\left(1 + \frac{V_0}{V_1 - V_3}\right)$$

$$V_0 = \frac{R_1(V_1 - V_2) + R_2(V_1 - (V_3 + 5\%V_3))}{R_1 + R_2}$$

$$T_2 + x_2\%T_2 = 0.915\,\tau_2 \qquad (V_3 + 5\%V_3)$$

And for a 5% decrease in V_3

$$T_2 - y_2\%T_2 = \tau_2 \ln\left(1 + \frac{V_0}{V_1 - (V_3 - 5\%V_3)}\right)$$

$$V_0 = \frac{R_1(V_1 - V_2) + R_2(V_1 - (V_3 - 5\%V_3))}{R_1 + R_2}$$

$$T_2 - y_2\%T_2 = 0.821\,\tau_2 \qquad (V_3 - 5\%V_3)$$

Now $x_2\%$ and $y_2\%$ can be determined.

$$\frac{T_2 + x_2\% T_2}{T_2} = \frac{0.915\,\tau_2}{0.842\,\tau_2}$$

$$x_2\% = 8.7\% \qquad (V_3 + 5\% V_3)$$

$$\frac{T_2 - y_2\% T_2}{T_2} = \frac{0.821\,\tau_2}{0.842\,\tau_2}$$

$$y_2\% = 2.4\% \qquad (V_3 - 5\% V_3)$$

5.4 Calculation from Experimental Results of the Change of Period of the Collector-Base Coupled Monostable Corresponding to Small Variations of Supply Voltages

In this section, the results of experiments on the dependence of the period of the astable on the supply voltage are summarized and compared with the theoretical results obtained in Section 5.3.

The experimental results obtained for variation in V_1 are as follows:

V_1	T_1	T_2
25.0	105 μs	165 μs
26.25	110 μs	165 μs
23.75	100 μs	166 μs

$$T_1 = 165 \mu s$$

$$T_1 + x_1\% T_1 = 110 \mu s$$

$$x_1\% = 4.2\% \qquad (V_1 + 5\% V_1)$$

The theoretical value obtained in Section 5.3 was 3%.

Also, for a 5% decrease in V_1

$$T_1 - y_1\% T_1 = 100 \mu s$$

$$y_1\% = 5\% \qquad (V_1 - 5\% V_1)$$

The theoretical value obtained in Section 5.3 was 4%.

Similarly for T_2, it can be seen that $x_2\% \approx 0$ and $y_2\% \approx 0$ $(V_1 \pm 5\% V_1)$.

The theoretical values for $x_1\%$ and $y_2\%$ were -2% and -5%, respectively.

The experimental results obtained for variation in V_2 are as follows:

V_2	T_1	T_2
15.00	105	165
15.45	105	165
14.55	105	172

For T_1, it is seen that $x_1\%$ and $y_1\%$ are equal to zero. The theoretical values for $x_1\%$ and $y_1\%$ are 1%. For T_2, $x_2\% = 0$, but $y_2\%$ will be

$$T_2 - y_2\%T_2 = 172\ \mu s$$

$$y_2\% = -4\% \qquad (V_2 - 5\%V_2)$$

The theoretical value of $y_2\%$ from Section 5.3 was zero.

The experimental results obtained for small changes in V_3 are as follows:

V_3	T_1	T_2
5.00	105	165
5.25	105	165
4.75	105	165

For T_1 and T_2, $x_1\%$, $y_1\%$, $x_2\%$ and $y_2\%$ are zero.

6. OPERATION OF INTEGRATED CIRCUIT MONOSTABLE MULTIVIBRATOR

A fifth possibility for the storage element is the integrated circuit monostable shown in Figure 23. The operation of this circuit is shown below.

With no trigger applied the logic relations are:

$$X_2 = Z_3 = \overline{Z_1 \cdot Z_2} = \overline{Y_3 \cdot X_3} = \overline{\overline{X_3 \cdot X_3} \cdot X_3} = 1$$

$$X_1 = X_2 = Z_3 = Y_3 = Z_1 = 1$$

$$X_3 = Y_1 = Y_2 = Z_2 = 0$$

When X_1 receives a negative pulse, X_3 and Z_2 switch to the 1 state. As a result, Z_3 and X_2 switch to the 0 state. After the X_1 negative pulse is removed, X_3 remains at 1, since X_2 is at 0. With Y_3 switched to 0, capacitor C discharges toward 0. When the voltage at Z_1 reaches 0, Z_3 switches back to 1. Thus X_3 returns to 0 and applies feedback to Z_2, causing it to switch states. Capacitor C recharges through R to the 1 state and the cycle is completed.

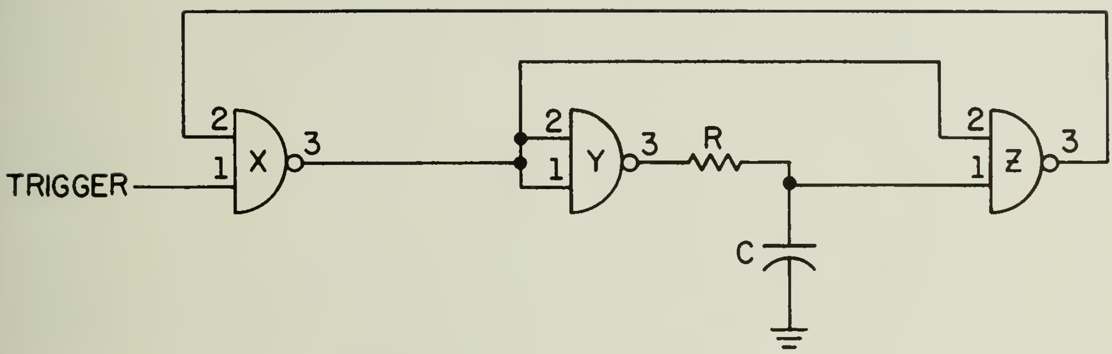


Figure 23. Integrated Circuit Monostable Multivibrator

6.1 Calculation of the Period of the Integrated Circuit Monostable Multivibrator

Only a rough calculation can be done for the period of the I.C. monostable, since the exact switching voltages of the NAND's used are not known. If a logical 1 level of -0.5 volts and a logical 0 level of -4.0 volts (these are levels which will assure a definite 1 and 0 at the output) are used, the equation for the 1 to 0 transition at Z1 is given below.

$$V_{Z1} = -5\ (1 - e^{-t/\tau_1})$$

At time T_1, (i.e. T_1 is time for 0 to 1 transition)

$$V_{Z1} = -4.5 = -5(1 - e^{-T_1/\tau_1})$$

$$T_1 = 2.3\,\tau_1 \qquad \text{where } \tau_1 = RC$$

This calculation only gives an order-of-magnitude value for the period.

Another restriction on the parameters is the size of the resistor R, since it must be small enough so that the voltage drop across it caused by the input current to Z1 does not cause a false input. The integrated circuits used are Tl 7400 quadruple 2-input

positive NAND gates. The maximum input current at the "1" level is 1 ma, therefore if a one volt drop in R can be tolerated, the resistor, R, cannot be greater than 100 Ω.

Now a rough value for C can be calculated. Assume $T_1 = 380\,\mu s$ as before, then

$$T_1 = 380\,\mu s = 2.3\ RC$$

$$C = 1.21\,\mu f$$

This is only an order-of-magnitude value for C.

6.2 Calculation from Experimental Results of the Change of Period of the Integrated-Circuit Monostable Corresponding to Small Variations of Supply Voltages

The actual values of R and C used for the I.C. monostable are given below.

$$R = 100\ \Omega$$

$$C = 2.2\,\mu f$$

Using these values, the experimental waveforms shown in Figure 24 were obtained. The power supply was -5 volts. As seen from the

oscillogram of Z1, $T_1 = 260\ \mu sec$ with the parameter values shown above. Hence, the value calculated in the previous section was not very accurate, but was an order-of-magnitude figure.

The variation in the period T_1 corresponding to variation in the power supply was also determined experimentally. The results are shown below.

V_1	T_1
5.00	260 μs
5.25	275 μs
4.75	235 μs

$$T_1 + x_1\%T_1 = 275\ \mu s$$

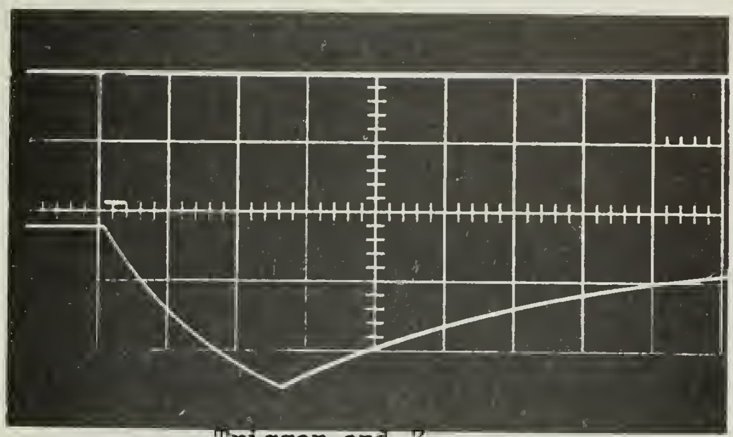
$$x_1\% = 6\% \qquad (V_1 + 5\%V_1)$$

$$T_1 - y_1\%T_1 = 235$$

$$y_1\% = 14.5\% \qquad (V_1 - 5\%V_1)$$

This period varies greatly with change in supply voltage. The time it takes for Z1 to return to a logical 0 also varies greatly with the supply voltage.

The waveforms obtained experimentally are shown in the oscillograms of Figure 24.

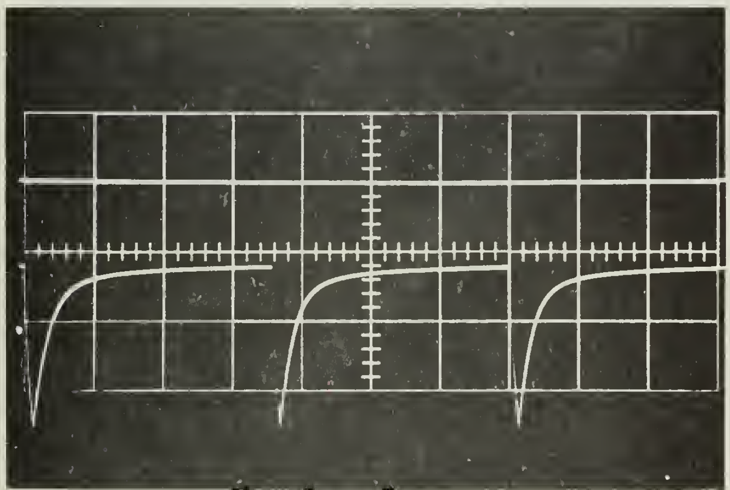


(a)

Trigger and Z_1

Time Base = 100μ sec/cm
Voltage Scale: upper trace = 0.2 volts/cm
lower trace = 0.1 volts/cm

Ground



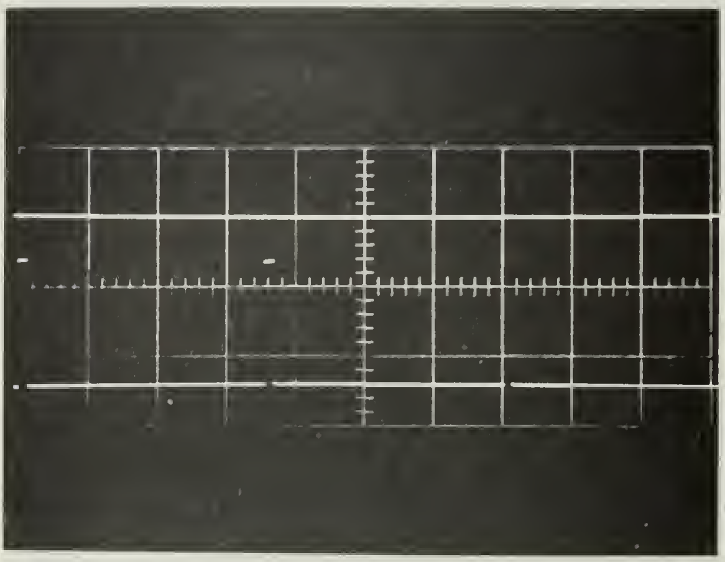
(b)

Waveform Z_1

Time Base = 2 msec/cm
Voltage Scale = 0.2 volts/cm

Figure 24. Experimental Waveforms of the Integrated Circuit Monostable Multivibrator

Ground



(c)

Waveform X_3

Time Base = 2 msec/cm
Voltage Scale = 0.2 volts/cm

Figure 24. Experimental Waveforms of the Integrated Circuit Monostable Multivibrator

7. CONCLUSION

The purpose of this thesis was to give the reader an idea of the Phastor analog storage system as it was conceived and implemented. Phastor is capable of storing four voltages which lie in the range, +10v to -10v. These voltages can be retained as long as the periods of the monostables remain constant. Storage times of eight hours have been observed in the model.

It is the author's suggestion that when this system is extended, all of the digital circuits be implemented with integrated circuits as this would cut down considerably on the power consumption of the system.

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13. ABSTRACT

An analog storage system has been designed using delay line techniques. The analog storage is accomplished by comparing the analog voltage to be stored with a voltage ramp in a comparison circuit; when equality between voltages is found an output signal from the comparison circuit triggers a monostable multivibrator which has the same period as the voltage ramp. The monostable multivibrator is made to retrigger by using feedback to control the gating of a trigger pulse. The system is capable of storing any voltage between approximately +10 volts and -10 volts to an accuracy of 1% of the full range.

Several possibilities for the storage circuit are investigated.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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